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**A PROCEDURAL GUIDE TO COGNITIVE  
TASK ANALYSIS:  
THE PARI METHODOLOGY**

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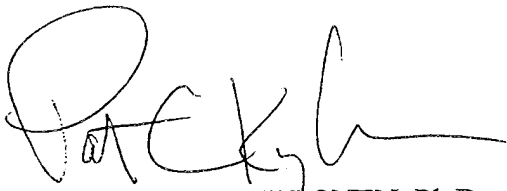
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13. ABSTRACT (Maximum 200 words) Developing effective instruction for complex problem-solving tasks requires analysis of the cognitive processes and structures that contribute to task performance. This report describes the data collection procedures associated with a cognitive task analysis technique known as the PARI (precursor, action, result, and interpretation) methodology. The methodology is being developed under the Basic Job Skills (BJS) program and constitutes one component of an integrated technology for developing and delivering training of cognitively complex tasks. The data collection procedures can be considered an extension of existing task analysis techniques and are based on studies of over 200 Air Force technicians in aircraft maintenance specialties whose primary task is troubleshooting. The procedures derived from these studies impose a structure on the knowledge acquisition task which captures the cognitive as well as the behavioral components of troubleshooting skill. The structured interview approach yields data that allow qualitative comparisons of problem-solving performances within and across technical skill levels. Such analyses have informed instruction developed under the BJS program by revealing the developmental course of skill acquisition and the components of expertise which are the training targets. More recent analyses have identified skill and knowledge commonalities across maintenance specialties and are informing training designed to facilitate knowledge transfer. A future goal of the BJS program is to examine the generality of the PARI methodology and the extent to which it can be applied to problem-solving tasks in nonmaintenance domains.				
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## PREFACE

This report describes a cognitive task analysis methodology developed under the Basic Job Skills Research Program. The work described was conducted by the Job Structures Branch of the Manpower and Personnel Research Division of the Human Resources Directorate, Armstrong Laboratory. It covers the period from January, 1985 through November, 1990.

We would like to thank the aircraft maintenance technicians assigned to Air Combat Command who contributed to the studies reported here, and particularly the expert technicians assigned to the laboratory to work on this project: TSgt Dennis Collins, MSgt Mark Gallaway, and MSgt Ron Kane. This work could not have been accomplished without their dedicated support.

## SUMMARY

Developing effective instruction for complex problem-solving tasks requires analysis of the cognitive processes and structures that contribute to task performance. This report describes the data collection procedures associated with a cognitive task analysis technique known as the "PARI" methodology. The methodology is being developed under the Basic Job Skills (BJS) program and constitutes one component of an integrated technology for developing and delivering training of cognitively complex tasks. The data collection procedures can be considered an extension of existing task analysis techniques and are based on studies of over 200 Air Force technicians in aircraft maintenance specialties whose primary task is troubleshooting. The procedures derived from these studies impose a structure on the knowledge acquisition task which captures the cognitive as well as the behavioral components of troubleshooting skill. The structured interview approach yields data that allow qualitative comparisons of problem-solving performances within and across technical skill level. Such analyses have informed instruction developed under the BJS program by revealing the developmental course of skill acquisition and the components of expertise which are the training targets. More recent analyses have identified skill and knowledge commonalities across maintenance specialties and are informing training designed to facilitate knowledge transfer. A future goal of the BJS program is to examine the generality of the PARI methodology and the extent to which it can be applied to problem-solving tasks in nonmaintenance domains.

# A PROCEDURAL GUIDE TO COGNITIVE TASK ANALYSIS: THE PARI METHODOLOGY

## I. INTRODUCTION

The purpose of this document is to provide a procedural guide to the use of a cognitive task analysis technique known as the PARI<sup>1</sup> methodology. This structured, thinking-aloud dialogue approach was developed as part of the Basic Job Skills (BJS) Research Program being carried out at the Air Force Armstrong Laboratory. Although the PARI methodology incorporates features of several existing task analysis techniques, its design was influenced by the specific research needs of the BJS program to investigate complex problem solving expertise in real world work environments. Section I of the guide examines these requirements as they relate to the program's goals and the shaping of the PARI technique. A discussion of alternative task analysis procedures follows in Section II. Section III provides a detailed description of the PARI procedure and examines how its features address particular BJS research requirements. Finally, Section IV discusses the broader uses of the PARI procedure as a research tool and as a general aid to instructional design and skill assessment.

### BJS Project Overview

#### Air Force Need and Research Response

The BJS Program is a large-scale research effort directed at examining the cognitive skills that allow individuals to interact adaptively with technologically complex systems. The need to understand and foster advanced technical skills has been made more urgent as a result of two parallel developments. First, as in most technical domains, the complexity of aerospace systems and equipment in the Air Force is continuing to increase at a phenomenal rate. This development poses an ever-growing challenge to Air Force personnel as they attempt to master their jobs by

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<sup>1</sup> PARI: Precursor, (or reason for Action), Action, Result, and Interpretation (of result) are problem-solving components of interest in diagnostic tasks.



acquiring adequate knowledge of equipment systems and repair experience during the relatively short period of their enlistment. At the same time, and in response to demands for greater versatility among technical personnel, the Air Force has instituted a program (the Rivet Workforce initiative) to restructure the aircraft maintenance workforce. This program stipulates that airmen operating and maintaining technical equipment are to become less specialized and demonstrate proficiency in several related job specialties.

While the first development demands the acquisition of in-depth system knowledge under considerable time constraints, the second development requires breadth and adaptiveness of knowledge and skill across multiple systems. The BJS program is a response to this twofold need. The goal is to develop an integrated skill analysis/instructional development technology that promotes both depth and breadth of proficiency in the maintenance of highly complex systems.

As the skill analysis component of the technology, the PARI technique (which is the focus of this report) is intended to allow both a broad and deep examination of problem solving expertise. Toward this end, the approach has evolved into a structured interview which occurs as experts pose problems to each other under realistic task performance conditions. A task analyst uses standardized interview questions to systematically probe the experts during and after solution generation. After the solution, the experts are asked to elaborate the solutions they have just generated in a series of rehash sessions. Here they are explicitly asked to address the factors considered (or reasons for) the problem solving decisions they made during the solution process. The PARI procedures thus yield fine-grained (but systematized) protocol data that capture both the solution steps and the supporting reasons to complex problems. From detailed protocol data, both precise targets for in-depth instruction as well as broad skill commonalities across domains can be identified. PARI output is then incorporated into curricula for learning environments that are designed to accelerate skill development as well as foster flexible, adaptive knowledge bases, thereby addressing the two pressing Air Force needs described above.

## Cognitive Task Analysis Methods to Represent Adaptive Problem Solving

Adaptive Expertise. A focus on adaptive expertise can be contrasted with skill analysis and instruction directed at developing routinized expertise. In the case of the latter, trainees are taught to perform specific procedures in a highly efficient manner in the recognizable situations of stable task environments (Hatano & Inagaki, 1984). Although perfectly appropriate for some tasks, such training does not equip a trainee to respond effectively to situations that are not explicitly addressed by the training. In today's technologically sophisticated workcenters, novel situations are frequently encountered, thus making adaptive problem solving a distinguishing hallmark of modern day technical skill. To perform well in dynamic, unstable task environments, the performer needs flexible knowledge and skill that are adaptable to novel problem situations. This implies an understanding of a job that goes far beyond knowledge of rote procedures for operating and maintaining a piece of equipment and includes knowledge of why a set of procedures is appropriate and effective for a given task. Conceptual support knowledge of this form empowers the human in dynamic, variable task environments by giving meaning to the steps of a procedure, by enabling the invention of new procedures, and by assisting in the reconstruction of forgotten procedures. Making the reasons for task performance explicit (i.e., specifying this conceptual support knowledge) is therefore a central goal of the PARI approach. This goal is being accomplished via several task analysis features.

Situated Problem Solving and the PARI Procedure. The PARI procedures revolve around **situated problem-solving** sessions where experts deploy knowledge in response to particular problem contexts and task demands. As they seek solutions, experts are probed for the reasons behind the actions they elect to take and for their interpretations of the results of their actions. In this way, the reasoning processes that are responsible for knowledge deployment are made apparent. The probes are part of a **structured interview** designed to reveal knowledge and skill in the context of their use. This approach contrasts with decontextualized task analysis interviews where knowledge is abstracted and detached from the problem-solving conditions under which it is normally applied. In the PARI interview, the full functional context of the domain is experienced so that the various intended uses of particular skills and knowledge structures (i.e.,

the reasons behind the procedures) are made explicit for teaching (Glaser et al., 1985; Gott, 1989).

Authentic performance contexts are achieved in a PARI interview through the **dyadic interactions** of pairs of experts.<sup>2</sup> One expert poses a problem to a second expert who is naive with respect to the problem's source. The second expert generates a solution, step by step, with the first expert providing the result of each step. The problem solving experience is thus a close approximation of the dynamic real world where causes of malfunctions and results of actions are not known in advance. Not surprisingly, experts solve problems much differently when they know the source of the problem. When they are naive to the problem source, they consider a much wider range of hypotheses and correspondingly search and access richer knowledge structures. As a consequence, an analysis of naive problem-solving is more fruitful in revealing all relevant knowledge bases, search procedures, and strategic deployment processes. The expert dyad represents a unique feature of the PARI methodology and serves to ground all knowledge elicitation firmly in authentic contexts.

Another PARI feature worthy of note is that the task analyst interviews **multiple experts** and gathers data on a **representative sample of domain problems**. The solutions that are produced are thus more likely to represent the full range of expert problem-solving performances and the collective domain knowledge of expert practitioners. Situated, problem-based learning environments can flow fairly easily from the products of a dyadic, representative task analysis such as this. Additional methodological features ensure that PARI interview data are both reliable and standardized.

Standardization and Codification of PARI Procedures. Standardizing and codifying any task analysis methodology is important to its continued utility, but the reasons are particularly compelling for codifying PARI procedures. The rationale is tied to the BJS research goal to represent both the depth and breadth of technical proficiency. In order to investigate skill and

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<sup>2</sup> Allan Collins, BBN and Northwestern University, provided the initial inspiration for this dyadic, in situ problem solving approach.

knowledge commonalities and associated processes of transfer, a comparison of task analysis results across job specialties is necessary. Within-job comparisons of expert and novice problem solving capabilities are also needed to examine the development of domain knowledge and problem-solving skill. Comparative analyses require data having a standard form. Imposing a structure on the PARI problem-solving sessions with the use of standard probes ensures uniform data structures across different task analyses, thereby facilitating these types of comparisons.

A related methodological issue concerns the implementation demands imposed on the task analysts who use the procedures. To understand these demands, it should be noted that the primary emphasis of the BJS program is to provide the Air Force with a technology for skill analysis and training development in technical domains. Since the purpose of such a technology is to allow the development of instruction by Air Force personnel who may not be cognitive psychologists, instructional design specialists, or even subject-matter experts, the technology should provide a principled and implementable method for both task analysis and instructional development by nonscientists. This practical concern underscores the need for well-codified procedures for (a) conducting task analysis studies, (b) compiling and interpreting resultant data, and (c) designing and developing training based on the findings. (This general issue of methodological codification will be discussed in detail in Section III of this guide.)

While the research requirements of the BJS program have significantly influenced the particular form of our task analysis procedures, the goal of capturing the conceptual knowledge underlying complex task performances (or reasons for procedural sequences) reflects a common objective of many cognitive analysis approaches. In the next section, we describe the cognitive components of skill that are typically targeted by such approaches. More specifically, we describe the components of problem solving expertise that have been consistently derived in BJS empirical studies and by research in cognitive psychology in general. The intent is to characterize more concretely the multifaceted knowledge structures that the PARI procedure is designed to capture.

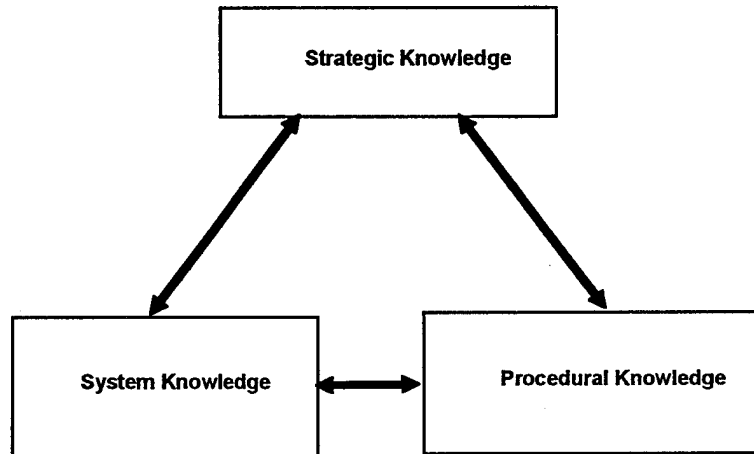
## Cognitive Components of Complex Problem Solving

### Ill-Structured Problem Solving

The diagnosis of faults in complex aerospace systems is an activity which can be characterized as ill-structured problem solving: there is no well-defined algorithm for problem solution, the goal structure of the solution may be poorly defined, and/or the criteria for evaluating solution acceptability may be weak (Newell, 1969). To date the study of ill-structured problem solving has yielded functional distinctions between different knowledge structures that contribute to skilled performance. These structures include procedural and declarative knowledge (knowing how as well as knowing that), and strategic decision factors or processes that are responsible for knowledge deployment and also serve an executive control function in problem solving. Gott (1989) summarizes the role of each of these cognitive components in solving problems involving the interaction of a human with a complex system:

Whether operating a word processor or diagnosing a faulty engine, the human performer is required to select and execute procedures to interact with an object to achieve a set of goals. The knowledge and processes that constitute that performance are (a) procedural (or how-to-do-it) knowledge, (b) declarative (domain) knowledge of the object (often called system or device knowledge), and (c) strategic (or how-to-decide-what-to-do-and-when) knowledge. With this decomposition it is assumed that procedural and device knowledge are organized and deployed by mechanisms such as the goals, plans, and decision rules that comprise strategic knowledge (Gott & Pokorny, 1987). This deployment capability serves a control function to enable what can be called dynamic, opportunistic reasoning. Ideally, this results in optimal solutions crafted in response to particular situations by applying just the right piece of knowledge at just the right time. (p. 100)

A model illustrating these interactions is depicted in Figure 1.



*Figure 1.* BJS Cognitive Architecture.

#### Coordination of Knowledge Structures

Experts appear to coordinate these multiple types of knowledge quite efficiently, generating plans and goal structures that deploy device models and procedures that virtually ensure problem solution. The goal-oriented nature of experts' problem-solving activity involves the consideration of multiple alternative solution paths and the judicious selection of alternative paths to pursue. Moreover, the solution search is (optimally) updated as new evidence about the probable source of the problem is uncovered. The lack of well-defined algorithms (as noted above by Newell) arises partly from the number of alternative methods available for solving such problems and from the fact that the expert's choice among these alternatives depends on information actively obtained through on-line hypothesis testing. Further, experts do not appear to consider every one of the virtually unlimited number of solution paths available in a complex problem (Glaser et al., 1985). Rather, they bring to bear a great deal of acquired knowledge to construct and constrain the problem/solution space. The development of various types of acquired knowledge and their roles

in problem solving will clarify the reasons for the functional distinctions researchers have made between procedural, system, and strategic knowledge sources.

Procedural Knowledge. The most readily observable aspects of task performance are the procedures that are executed in carrying out the task. Taking measurements, swapping components, and running diagnostic tests are examples of procedures commonly executed in tasks like electronic troubleshooting. While knowledge of how to execute these procedures is a prerequisite for troubleshooting expertise, it alone cannot account for such expertise. A variety of expert-novice studies have shown that when technicians are tested on basic troubleshooting operations outside the context of solving actual problems, differences in skilled and unskilled subjects' performance are not substantial (Gitomer, 1984; Glaser et al., 1985; Soloway, 1986). It is experts' ability to select procedures in such a way as to optimize the efficiency of troubleshooting that markedly distinguishes them from unskilled technicians. This ability in turn appears to depend heavily on knowledge of how the system or device works.

Declarative (System) Knowledge. Declarative (or how-it-works) knowledge appears to provide the basis for the adaptiveness that characterizes technical expertise in domains dominated by ill-structured problems. Knowing why procedures work, for instance, allows known procedures to be adapted to novel situations and to be reconstructed if forgotten. Much of the research directed at examining how declarative knowledge enables this flexible use of procedural knowledge has been concentrated in the domain of complex system operation and maintenance. This work has suggested a close association between one's understanding of why procedures work and knowledge of how the system itself works.

In experiments reported by Kieras and Bovair (1984), subjects were asked to operate a simple control panel device. One group learned a set of operating procedures by rote while the second group was provided information about the device's topology and internal structure prior to receiving training on procedures identical to that of the first group. The second group was thus provided with a "device model" and appeared to use this model for learning the procedures and for performing the task: they learned the procedures faster, retained them more accurately, executed them faster, and simplified the inefficient procedures more often than the rote group. In

a second study, subjects who either had no training at all or had received device topology instruction were asked to operate the device; neither group received explicit training in operating procedures. In contrast to subjects in the no-training group (who learned how to operate the device by trial and error), those in the device model group were able to operate the device almost immediately.

This study lends striking support to the view that for domains where problem-solving activity is directed at the operation and maintenance of equipment systems, the technician's understanding of the system constitutes critical content of the declarative knowledge base. Such knowledge includes facts about the system's internal structure, the functions of various system components, how components operate and interact; in short, how the system works. As problems are solved, relevant facts are selected from this base and organized to form a device model that can be elaborated as new facts about the device's current behavior are discovered, and mentally manipulated to formulate hypotheses and determine the next appropriate step in the solution.

The contribution of system understanding or device knowledge to troubleshooting expertise is further documented by other studies comparing the depth and quality of this knowledge in expert and novice technicians (Tenney & Kurland, 1988; Gitomer, 1984; Glaser et al., 1985; Means & Gott, 1988.) In general this body of work supports the conclusions summarized below regarding expert and novice system knowledge, strategic knowledge, and associated problem solving.

There are striking differences in the quality of novice vs expert device representations as well as the ways that experts and novices use their knowledge of the system to construct and constrain the problem space. Whereas experts are able to relate symptoms to possible inoperative system functions, novices tend to relate symptoms to equipment components that are located in the immediate physical vicinity of the initial symptoms. This suggests a deep vs surface structure difference in expert and novice device models. The deep structure models of experts allow an initial problem representation that incorporates functional areas of the equipment that could be responsible for the observed symptoms. Experts then solve the problems by systematically and



efficiently eliminating each of these areas as the probable source. Novice solutions on the other hand, tend to be characterized by an initial focus on components that are physically near the component displaying the symptom, regardless of the functional likelihood that proximal components could be the cause. This is consistent with the superficial model of the system they presumably possess. If such localized options fail to isolate the fault, subsequent searches by novices appear to be random (Gott, 1989; personal communication). Due to their lack of system understanding, novices are apparently unable to think of the equipment in terms of functional units which would help them generate effective plans for an efficient investigation.

Strategic Knowledge. Differences in strategic decision making by expert and novice troubleshooters have also been established in comparative studies of problem solvers (Gitomer, 1984; Glaser et al., 1985). Strategic knowledge is used to select and deploy relevant system and procedural knowledge for the purposes of establishing goals, planning solutions, evaluating the outcomes of steps in the solution, and monitoring the progress of the solution. The compiled empirical evidence suggests that differences in strategic knowledge are related both to the deeper and more elaborated structures of the expert's system knowledge and to problem solving strategies which direct the search for solution-relevant information.

The expert's greater knowledge of the system increases the number and quality of alternative hypotheses considered, while facility with basic troubleshooting operations allows these hypotheses to be tested in a variety of ways. The expert thus has a number of alternative solution paths available and the resulting procedural flexibility permits the construction and on-line refinement of a troubleshooting plan and associated operations that are specifically adapted to the problem being solved. In sum, experts are able to engage in dynamic, opportunistic reasoning because they have richer system knowledge bases and a wider range of tools (operations) for implementing their plans.

This interpretation acknowledges the dependence of strategic processing on the content and organization of specific device and procedural knowledge structures (see also Chi, Glaser, & Rees, 1982; Greeno, 1980). This is in contrast to a view of the strategic component of expertise

as domain-independent or general (weak) problem-solving heuristics. A result reported by Glaser et al. (1985) illustrates this distinction and supports the "knowledge-based" view of expert strategic decision making. These investigators examined the generation of plans by skilled and less skilled avionics technicians in a verbal troubleshooting task. While the two groups did not differ with respect to the frequency of plan generation, the quality of these plans varied in predictable ways:

Both higher and lower skill subjects were planful. The differences arise only when the utility of the plan for solving the problem is considered. Put another way, the less skilled subjects have equivalent "weak" methods to their more skilled colleagues but are way behind on stronger problem-solving methods, methods particularized to the specific technical domain (p. 283).

Thus, although domain-independent strategies (weak methods) may be used by both experts and novices, it is the experts who deploy particularized, strong methods.

It is often strategic knowledge that is overlooked in standard textbook presentations of course material. For example, in examining instructional materials for geometry courses, Greeno (1978) observed that of the three components necessary for problem solving in geometry, strategic knowledge was neither explicitly taught by teachers nor directly treated in textbooks. Correspondingly, Chi, Glaser, and Rees (1982) note that when problem solving strategies are studied in the context of relatively knowledge-free tasks (e.g., in studies using puzzle problems), limited insights are gained into principles that guide the search of a large knowledge base. In both cases, the relationship between knowledge of the domain and the strategies used to solve problems fails to become established. In sum, the strategic knowledge that enables planning and decision making by expert problem solvers may be overlooked when domain knowledge is analyzed outside the context of its intended use, i.e., decontextualized from actual problem conditions. The importance of capturing the procedural, declarative, and strategic components become clearer as the design of instruction is contemplated.

## The Cognitive Analysis of Expertise as Input to Instruction

### Cognitive vs Behavioral Task Analysis

Cognitive task analyses were first used to inform instructional development during the mid seventies (Greeno, 1976; Resnick, 1976) as psychological theories of cognitive processing became sufficiently mature to yield specific analytic procedures. Prior to that time, the dominant approach to task analysis could be classified as a "behavioral-rational" method (Gott, 1986; Gagne, 1974; 1977). A brief comparison of these approaches may make clearer the utility of a cognitive analysis.

One distinguishing feature of the two approaches is their differing orientations to instruction. Whereas the purpose of a behavioral-rational task analysis is primarily to specify the component steps of the observable behaviors as targets of instruction, e.g., how to operate a voltmeter (Anderson & Faust, 1973), a cognitive analysis is targeted at the underlying psychological processes and knowledge structures that are required to produce the correct overt behaviors at the appropriate time, e.g., understanding what a voltmeter does, when its use is indicated, what its resultant data reveal, and so forth (Greeno, 1976). Thus, while instruction based on behavioral analyses may emphasize the specific behavioral steps required to perform a task, instruction based on a cognitive analysis also teaches the psychological underpinnings of these behavioral steps, or the conceptual support knowledge that both explains the solution and fosters adaptiveness, as discussed earlier. This difference in instructional orientation is reflected in the content of the knowledge bases produced by the two types of task analysis.

Traditionally, emphasis has been placed on the identification of observable behaviors as instructional targets; therefore, procedural (or how-to-do-it) knowledge is readily captured in behavioral-rational analyses. However, other equally important forms of knowledge used by experts in complex problem solving tasks may be ignored. For example, declarative (or factual) knowledge and strategic knowledge may have no outward performance manifestations and are thus difficult to capture with more traditional methods. The benefits of cognitive models that

specify such unobservable psychological processes and knowledge structures are supported by a growing body of empirical data. The evidence shows that on knowledge-rich tasks, the typical novice deficiencies are not procedural (or how-to-do-it knowledge), but rather tend to be gaps in declarative knowledge bases and uncertainties about when to deploy specific pieces of knowledge (Glaser et al., 1985; Soloway, 1986; Gitomer, 1984).

Because cognitive analyses examine all relevant knowledge sources rather than focusing exclusively on the single source that is most directly tied to observable behaviors (i.e., procedural knowledge), they yield more detailed representations of tasks to be used as instructional targets (Gott, 1989). In these representations, the goals to which procedural knowledge applies and the strategic processes that are responsible for the organization, coherence, and general execution of the performance are clearly established. Knowledge is not only directly tied to its uses in the real world, but knowledge that is typically tacit (including goals, strategies, and assumptions) is made explicit for teaching. Cognitive analysis data as input to instruction thereby offers the potential for a more complete treatment of the multifaceted forms of knowledge used in complex problem solving. In turn, adaptive performance becomes a more realistic instructional goal.

Pedagogical design can be further informed by the results of cognitive analyses that reveal developmental aspects of the skill acquisition process, specifically, the differences among individuals at different proficiency levels (Gott, 1986). The way that knowledge is acquired and organized and how skills are developed over time can be captured and used to inform the sequencing of instructional events. In that way students are naturally taken through successive approximations of mature practice as they learn how to perform increasingly complex tasks (Gott, 1989).

We have argued thus far that training targeted at modern day expertise must make explicit the multiple types of knowledge that contribute to overt skill. Cognitive task analyses can be viewed as extensions of traditional behavioral techniques in this regard. The following discussion examines instructional systems that have been informed by cognitive models of skill acquisition and performance.

## Instructional Trends

In their recent reviews of cognitive theory-based instructional systems, both Glaser and Bassok (1989) and Gott (1989) note the contribution of cognitive task analysis methods to the development of advanced instructional systems. They point out, however, that few instructional designers have attempted to integrate the multiple knowledge sources that contribute to skilled performance or to make these knowledge structures explicit to the student. Instead, instruction tends to focus on the acquisition of a single (or sometimes dual) skill component, (e.g., procedural skill and goal structure knowledge in Anderson's LISP tutor [Anderson, Boyle, & Reiser, 1985; Anderson & Reiser, 1985] or strategic planning and self-monitoring in the reading comprehension program of Brown and Palincsar [1984; 1988]). Next we consider some of the limitations of instructional systems that represent this more common single or dual component instructional approach.

Researchers' attempts to represent domain knowledge in a form that would yield executable models of task performance provided the basis for several systems representing the cognitive approach to instruction (O'Shea, 1979a; 1979b; Clancey, 1979a; 1979b; Sleeman & Smith, 1981; Anderson, et al., 1985; Anderson & Reiser, 1985). The cognitive performance models underlying these "tutors" incorporated production rules as the computational structure in which knowledge was represented. Production rules can be described as condition-action pairs: they state the conditions under which a particular action is to be taken, as well as the action itself. Thus, the model can be said to represent knowledge of both "how-to-do-it" (procedural knowledge) and "when-to-do-it" (strategic knowledge).

Although quite powerful in terms of their ability to solve problems, production systems have difficulty in providing a sound theoretical basis for humans' ability to solve ill-structured problems. First of all, in domains characterized by such problems, the number of rules required to represent all goal states and their associated actions would be virtually unlimited. Given the assumption of such tutors that production rules are the units of knowledge to be acquired, Gott (1989) notes that the student must learn a large set of independent, situation-specific rules with limited

generalizability, thus raising the question of whether adaptability to unfamiliar situations requires knowledge of a different sort. Further, Rouse (1982) states a serious concern with this type of "procedural knowledge" acquisition in complex real world domains:

. . . the proceduralization approach is fundamentally limited by the fact that one can seldom anticipate all of the events that may occur in a particular system. Thus, the operators and maintainers inevitably encounter an event for which there is no procedure, or a combination of events for which it is not clear which procedure, if any, should be used. In such situations, proceduralized training is of no use (p. 104).

In fact, Anderson himself has noted that the production-system approach is more suited to "algorithmically tractable domains" (1987) and that in some instances, "more generalized declarative knowledge may be desired" (1988).

The limitations of instructional systems that require students to learn large numbers of procedures or rules by rote were made clear in field tests of GUIDON, a medical diagnosis tutor based on an expert system called MYCIN. Students who participated in these tests had difficulty understanding and remembering MYCIN's rules. Because MYCIN did not use or represent either the reasoning strategies used by humans in medical diagnosis or knowledge of how the human system works, these knowledge components (which are required in diagnostic problem solving by humans) could not be communicated to students by GUIDON. Students could not make sense of MYCIN's production rules so as to integrate them into a useful body of knowledge (Clancey, 1984). Although MYCIN's rules are a "machine-efficient" framework for the representation of knowledge, they represent "compiled" expertise which makes them too obscure for students to comprehend and retain (Wenger, 1987).

More recent work by Clancey and his colleagues has focused on the decompilation of expertise and modelling the reasoning strategies used in problems of heuristic classification. In the newer systems resulting from this work (e.g., NEOMYCIN and GUIDON2) reasoning

strategies and different types of knowledge (e.g., general principles, common world facts, definitional and taxonomic relations) are discreetly represented so that the diagnostic problem solving process can be meaningfully communicated to students.

### PARI Data as Input to Instruction

The PARI approach to instructional development has benefitted from the lessons of both behavioral and early cognitive instructional approaches. The methodology reflects the need to capture the cognitive underpinnings of complex task performance by human problem solvers, in order to identify the knowledge that is required for human students to understand the problem solving process. The features of the methodology outlined earlier in this section (e.g., situated problem solving and dyadic interaction) enable the specification of procedural, declarative, and strategic knowledge, as well as the coordinated deployment of all three knowledge components during dynamic, opportunistic problem solving.

The ultimate purpose of the PARI procedure is to provide models of a range of performances that can then be used to guide the design of instructional systems which target the acquisition and integration of all three skill components. There are of course other task analytic procedures that are directed at producing models of performance for various uses. Some of these procedures also focus on underlying cognitive processes and knowledge structures as a way to explain observable behaviors. Selected alternative methods will be briefly reviewed in the following section in order to sharpen the rationale for our development of the PARI approach.

## II. ALTERNATIVE TASK ANALYSIS APPROACHES

### Instructional Systems Design (ISD)

#### Purpose

Instructional systems design or the ISD approach is a methodology that has been widely used by the Air Force since 1972 for designing and developing Air Force training programs (Devries, Eschenbrenner, & Ruck, 1980). As a task analytic approach, the ISD procedure has been described as a general-purpose tool suitable for the decomposition of a wide variety of tasks. The tasks to be decomposed are determined by a coarse-grained analysis of a job which identifies the duties of that job (e.g., the job of vehicle mechanic involves duties such as adjusting and repairing brakes, tuning engines, repairing electrical systems, and so forth). Each of these duty categories comprises a set of tasks (e.g., tuning engines might require distributor repair, plug replacement, carburetor repair, etc.). Task analysis or decomposition then involves two components: (a) identifying the subtasks that define task performance and (b) specifying the skills and knowledge underlying each subtask.

#### Procedure/Result

The identification of subtasks is accomplished through the observation of the task being performed by a subject-matter expert under simulated or actual job performance conditions. The analyst lists the steps or overt acts in the task, indicating exactly what is done and how the steps are performed, whether and how any equipment is used, and any decisions that are required during the procedure. The major steps identified in the procedure correspond to subtasks which become the focus of the next stage of the analysis. In this stage, the declarative knowledge and physical and manipulative skills required to perform each subtask are listed. The analyst may rely on task observation, studies of job documentation, and the judgment of the subject matter expert in identifying supporting skills and knowledge. The task analysis documentation form and resultant data are illustrated in Table 1.



Table 1

*ISD task analysis documentation form (adapted from DeVries, Eschenberenner, & Ruck, 1980)*

STS/CTS TASK: ISOLATE DEFECTIVE PARTS IN/ON POWER SUPPLY CIRCUIT					
BEHAVIOR: ISOLATE DEFECTIVE PARTS IN/ON POWER SUPPLY CIRCUIT					
CONDITIONS: GIVEN MULTIMETER, O'SCOPE AND KAM'S 175 & 176					
STANDARDS: WITHIN 15 MINUTES EACH					
REFERENCES KAMS 175 & 176, AFRAM 525, KAO 81					
STEP NO.	STEP (SUBTASK/DECISION QUESTION)	DECISIONS		GO TO STEP	SUPPORTING SKILLS & KNOWLEDGES
		YES	NO		
1	CHECK FUSE FOR CONTINUITY WITH MULTIMETER			2	S - USE OF MULTIMETER K - LOCATION OF FUSE
2	IS FUSE CONTINUOUS	3	5		K - CRITICAL READING ON MULTIMETER
3	CHECK RECTIFIER CIRCUITS WITH OSCILLOSCOPE			4	S - USE OF OSCILLOSCOPE K - RECTIFIER DIODE OUTPUTS K - USE OF KAM'S 175 & 176
4	CHECK REGULATOR CIRCUITS WITH MULTIMETER			STOP	S - USE OF MULTIMETER K - REGULATOR VOLTAGE OUTPUTS K - USE OF KAM'S 175 & 176
5	CHECK TRANSFORMER WITH OSCILLOSCOPE			6	S - USE OF OSCILLOSCOPE K - HIGH VOLTAGE SAFETY PRECAUTIONS K - TRANSFORMER ACTION K - USE OF KAM'S 175 & 176
6	CHECK FILTER CIRCUITS WITH MULTIMETER			STOP	S - USE OF MULTIMETER K - CAPACITIVE REACTANCE K - USE OF KAM'S 175 & 176

The behavior (or task) of interest in this example is to "isolate defective detailed parts in/on power supply circuits." DeVries et al. (1980) refer to this behavior as a "variable sequence, equipment oriented task," and they use a flowchart to diagram the decision sequence (see Figure 2). Associated with each subtask/decision question are the supporting skills and knowledge the task analyst either observes or infers from the technician's behavior and/or associated task documentation. The output from an ISD analysis closely parallels the condition-action rules discussed earlier as "how-to-do-it" or procedural knowledge. The units of knowledge to be acquired in both cases are procedural rules, e.g., "If the goal is to isolate a defective part in a power supply circuit, then check the fuse for continuity using a multimeter; if the fuse is continuous, check rectifier circuits using an oscilloscope; and so forth." What is not clear from this type of analysis are the reasons underlying the sequence of procedures, e.g., why start with the fuse and then go to the rectifier circuits? More explicit information about strategic decision factors and the specific device models of the power supply that are being used would be required to flesh out the underlying reasons (conceptual support knowledge) for this particular task performance.

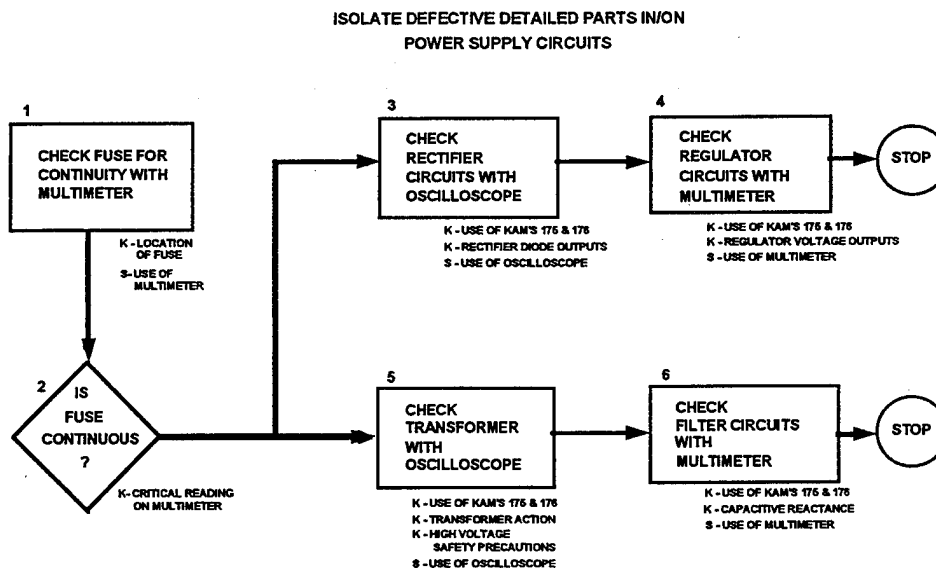


Figure 2. ISD task analysis flowchart (adapted from DeVries, Eschenbrenner, & Ruck, 1980).

### Relationship to the PARI Approach

There are several possible reasons why device models and strategic knowledge are not targeted more directly by the ISD approach. The relatively simple nature of the procedure being analyzed in this example may make any deeper cognitive analysis of the task unjustifiable, i.e., not "cost effective" for instructional development purposes. In addition, the format of the ISD methodology is such that the performer knows in advance the location of the source of the problem. This advance knowledge removes the need for the problem solver to investigate alternative hypotheses, which in turn leaves "unactivated" (and thus undocumented) many strategic decision control processes and alternative device models.

As a consequence, the ISD task analysis methodology may be most useful for stable task environments where task performance is algorithmic and therefore, predictable enough that relatively few cognitive demands are imposed on the performer. For example, one can imagine the prespecified steps in Table 1 being learned for purposes of routinized efficiency because of the relatively simple device that is the object of the performance. However, on more complex

devices, prespecification of all procedural sequences is not feasible. Such tasks are ill structured and thus it becomes important to specify the conceptual support knowledge and top-level control knowledge (for a set of procedural steps) so that the learner acquires the capability to make informed decisions when forced to generate new solutions to novel problems. For these reasons, the PARI methodology is viewed as complementary to the ISD approach.

### GOMS (Goals, Operators, Methods, Selection Rules) Analysis

#### Purpose

The GOMS analytic approach was developed for modelling a specific type of task performance, namely, human-computer interactions (Card, Moran, & Newell, 1983). The approach yields an executable computer model of a task which is constructed by (1) performing a task analysis to specify the constraints imposed on human behavior by the nature and features of the task environment and (2) applying certain empirically derived estimates of the user's processing speed, short-term memory capacity and duration, and other cognitive parameters. The resultant model accounts for differences in task performance in terms of the cognitive demands placed on the user by variable features of alternative task environments. A GOMS analysis of a task such as text editing (in the word processing domain) can be used, for example, to assess the influence of alternative interface designs or documentation formats on task performance.

#### Procedure/Result

The information-processing activity of the user is modeled in a GOMS task analysis by four components: Goals, Operators, Methods for achieving goals, and Selection rules for choosing among alternative methods. Goal statements decompose and define the task as a hierarchy of subgoals, which correspond to component subtasks. For example, in the text editing domain, goals might range from a top-level goal of Edit manuscript to a lower-level subgoal such as Locate line. Each goal has associated with it one or more Methods for achieving it. Methods are made up of a sequence of Operators which are executed serially to satisfy the goal-subgoal

hierarchy. In the context of text editing, operators might include elementary cognitive (or perceptual or motor) actions such as Insert-text, Scroll-to, Type, and Verify-edit. The operator sequence or method corresponds to a procedure for accomplishing a subtask.

For example, if the goal is to Insert Text, the user may not know where to make the insertion, and so the appropriate method might begin with a rather global action to consult the manuscript to locate the insertion spot (Operator 1). The next action might be to select the target location by using one of several methods available, for example, scrolling or jumping (Operator 2). Once the spot is located, the user would issue the Insert command to the editor (Operator 3 of the method). Then s/he either remembers the text to be inserted or consults the manuscript (Operator 4). Finally, the user types in the new text (Operator 5) (Card et al., 1983).

The final component of the GOMS model is the set of Selection Rules. These rules are used as a control structure for deciding which among the available methods to use in meeting a particular goal. In GOMS notational terms, each Selection Rule takes the form, "If X is true in the current task situation, then use method M." (Illustrative Goals, Operators, Methods and Selection rules from a GOMS model are shown in Table 2.) A GOMS model is constructed from data collected as a computer user performs a task such as editing a manuscript. The data may be available from videotaped records of the user's behavior and time-stamped files of keystrokes or from input from other devices such as a mouse or joystick. The data are then coded into a protocol of operator sequences, which yield, among other indicators, detailed information on the time required to achieve the component goals of the task.

#### Relationship to the PARI Approach

Because the GOMS technique was developed for the purpose of modelling computer tasks, much of the performance being analyzed is cognitive activity that is not directly observable (e.g., decisions involving method selection, or the execution of operators such as "verify edit"). It is important to note however, that in representing computer usage knowledge, a GOMS analysis resembles an ISD task analysis in the sense that procedural or how-to-do-it- knowledge

Table 2

*Goals, Operators, Methods and Selection Rules from a GOMS model of a text editing task (Card, Moran, & Newell, 1983). \**

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GOALS:

GOAL: Edit manuscript  
 GOAL: Edit unit task  
 GOAL: Acquire unit task  
 GOAL: Insert (insertion point key, new text)  
 GOAL: Delete (old text key)  
 GOAL: Replace (old text key, new text)  
 GOAL: Move (insertion point key, old text key)  
 GOAL: Select target (manuscript position, position type, visual search target)  
 GOAL: Point to target (manuscript position, visual search target, select?)  
 GOAL: Point there (screen position, text type, select?)

OPERATORS:

Get from manuscript (desired information, attribute)  
 Get from display (desired information, attribute, manuscript position)  
 Scroll to (line in manuscript)  
 Point (screen position, text type, select?)  
 Jump to (line in manuscript)  
 Insert text  
 Delete text  
 Replace text  
 Type (new text)  
 Execute (task)  
 Verify Edit

METHODS:

One at a time method  
 Acquire execute verify method  
 Read task in manuscript method  
 Insert command method  
 Delete command method  
 Replace command method  
 Delete insert method  
 Zero in method  
 Rough point method  
 Character point method  
 Word point method  
 Text segment point method  
 Insertion point method  
 Point without scrolling method  
 Scroll and point method  
 Jump method

SELECTION RULES:

Rough loc rule  
 Text segment rule  
 Character point rule  
 Word point rule  
 Insertion point rule  
 Top 2/3 rule  
 Bottom 1/3 rule  
 Off Screen rule

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\* Note From *The Psychology of Human Computer Interaction* (p. 210) by Card, Moran, & Newell, 1983, Hillsdale, NJ: Erlbaum. Copyright 1983 by L. Erlbaum Associates. Reprinted with permission.

dominates the model. In addition, certain types of knowledge are assumed to be irrelevant to the human-computer interaction. For example, system knowledge (i.e., how the computer works) is not required to interact effectively with the system. Nor is knowledge of the domain to which the computer task applies considered relevant. One needn't necessarily have domain knowledge about rainfall in South America in order to edit a manuscript on the subject. The assumption is that such knowledge does not affect the ability of the user to interact with the system.<sup>3</sup> Thus, a GOMS analysis models human-computer interaction as relatively domain-independent procedural skills. The PARI methodology can be considered an extension of this approach with its applicability to knowledge rich tasks where three types of knowledge are coordinated for task performance -- the procedural skills themselves plus underlying conceptual support knowledge consisting of system and strategic knowledge structures.

### The Knowledge-Engineering Approach

#### Purpose

Like a GOMS analysis, the goal of the knowledge engineering approach is to produce an executable (computational) model for performing cognitive tasks of interest. Applications have typically been in the development of expert systems, which are designed to aid nonexperts in task performance and decision making. Examples of domains targeted in expert system development include medical diagnosis (e.g., MYCIN [Shortliffe, 1976]; MDX [Chandrasekaran et al., 1979]; Puff [Feigenbaum, 1977]; KMS [Reggia et al., 1980]), oil and mineral exploration (e.g., Dipmeter Advisor [Davis et al., 1981]; Prospector [Hart et al., 1978], computer configuration (e.g., R1 [McDermott and Steel, 1981], and analysis of electrical circuits (e.g., EL [Stallman & Sussman, 1977]).

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<sup>3</sup> However, see Kieras and Polson (1985) for a description of how procedural knowledge that is captured in a GOMS analysis can be used to define device knowledge that is relevant for a task, i.e., device knowledge which allows the user to infer the exact operating procedures of the system.

It is important to underscore the use of expert systems as performance aids, not instructional systems. This intended utility influences the types of knowledge that are elicited via knowledge engineering techniques. More specifically, the role of an expert system is to execute a task, not explain why the task is executed in a particular way for purposes of human learning. As a consequence, conceptual support knowledge that provides reasons for task execution is of little interest to the knowledge engineer.

### Procedures/Results

The knowledge engineering process can be conceived in terms of five stages: identification, in which the subject-matter expert and a knowledge engineer work together to determine the characteristics of the problem(s) to be addressed by the expert system; conceptualization, in which the key concepts in the domain of interest, i.e., components of system or declarative knowledge, are explicated, along with concept interrelationships and the information-flow characteristics needed to describe problem solving in the domain; formalization, in which the key concepts and relations are transformed into a formal representation (computer) language (i.e., domain-specific concepts are defined in the language of the expert system); implementation, in which the procedural operations and reasoning processes (e.g., rules, frames, networks, or predicate calculus) that make use of the concepts are formulated; and finally, testing, in which the resultant executable expert model is evaluated and revised to conform to the performance standards established by the human experts in the problem domain (Hayes-Roth, Waterman, & Lenat, 1983).

Two approaches to knowledge engineering have dominated expert system development of this type. The traditional approach, verbal protocol analysis<sup>4</sup>, involves knowledge elicitation grounded in observable, interrogatory, and intuitive techniques (Waterman, 1985). Experts are asked to think aloud as they solve problems or to specify what they know about a given concept.

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<sup>4</sup> The use of verbal protocol analysis has not been restricted to expert system development but extends to the study of problem solving in general. These methods will therefore be discussed in detail in a later section.

A knowledge engineer probes the expert for explicit information regarding problem solving performance and has the responsibility for representing the expert's task execution according to some predetermined formalism or representational (computer) language. Table 3 illustrates raw data from a verbal protocol session represented as condition-action rules. In expert system development of this type, the knowledge engineer is usually not an expert in the subject matter domain but has the computer skills required for programming the knowledge base in the chosen representation language.

A second approach to knowledge engineering is the use of automated tools for knowledge acquisition and validation or testing of the resultant knowledge base. The purpose of automating the knowledge engineering task is to allow the expert to interact directly with a computer system rather than work through an intermediate layer, i.e., a human knowledge engineer. Automated tools embody certain underlying assumptions about the particular representational scheme to be used by the expert system (e.g., rules, frames, networks, predicate calculus) and the control strategy employed for searching the knowledge base. In other words, the expert does not have to specify how knowledge is used by the system since it is inherent in the representational structure and control mechanisms. This approach allows the expert to focus exclusively on generating the knowledge required to produce expert solutions and eliminates the need for a knowledge engineer with sophisticated programming expertise, since the knowledge acquisition tool automatically transforms the input into the representational language that is to be used in the targeted expert system. The choice of a representational scheme in expert system development involves consideration of which scheme yields the most efficient system performance. That choice, in turn, gives structure to both the elicitation and interpretation of domain knowledge. To date, the most successful expert systems embody rule-based representation schemes (Boose, 1986).

#### Relationship to the PARI Approach

We noted in an earlier section that the representational structure used in an expert system may not be compatible with the goal of teaching. Recall that the limitations of GUIDON as a tutor had primarily to do with the rule-based representation of domain knowledge in MYCIN, the



Table 3

*Verbal protocol data and resulting procedural rules (adapted from Buchanan et al., 1983).*

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### RAW VERBAL PROTOCOL DATA

(From interview on identifying chemical spills and their sources, Buchanan et al., 1983)

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#### KNOWLEDGE ENGINEER:

Suppose you were told that a spill had been detected in White Oak Creek one mile before it enters White Oak Lake. What would you do to contain the spill?

#### EXPERT:

That depends on a number of factors. I would need to find the source in order to prevent the possibility of further contamination, probably by checking drains and manholes for signs of the spill material. And it helps to know what the spill material is.

#### KNOWLEDGE ENGINEER:

How can you tell what it is?

#### EXPERT:

Sometimes you can tell what the substance is by its smell. Sometimes you can tell by its color, but that's not always reliable since dyes are used a lot nowadays. Oil, however, floats on the surface and forms a silvery film, while acids dissolve completely in the water. Once you discover the type of material spilled, you can eliminate any buildings that either don't store the material at all or don't store enough of it to account for the spill.

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### RAW DATA CONVERTED TO CONDITION-ACTION RULES

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To determine spill material:

- [1] If the spill does not dissolve in water and the spill does form a silvery film, let the spill be oil.
  - [2] If the spill does dissolve in water and the spill does form no film, let the spill be acid.
  - [3] If the spill = oil and the odor of the spill is known, choose situation:
    - if the spill does smell of gasoline, let the material of the spill be gasoline with a certainty .9;
    - if the spill does smell of diesel oil, let the material of the spill be diesel oil with certainty .8.
  - [4] If the spill = acid and the odor of the spill is known, choose situation:
    - if the spill does have a pungent/choking odor let the material of the spill be hydrochloric acid with certainty .7;
    - if the spill does smell of vinegar let the material of the spill be acetic acid with certainty .8.
- 

expert system whose knowledge the tutor was intended to convey to students. MYCIN did not require knowledge of human system functioning, nor did it require human-like reasoning strategies to perform successfully. Without such knowledge, however, students were unable to

acquire and retain MYCIN's rules. The point here is that the form of data resulting from a task analysis for expert system development may be of limited use if one's goal is to teach a human how to execute the task rather than to program a computer to execute it.

Although knowledge-engineering tools and the PARI methodology were developed for different purposes, they do have one critical feature in common; that is, the type of problem-solving activity that is typically the focus of the knowledge acquisition process. Both procedures examine problems that are ill structured: their solutions are not based on algorithms but on a collection of informal knowledge acquired through experience. The design of certain knowledge-engineering tools (e.g., TEIRESIAS; Davis, 1982) and the PARI procedures have been influenced in the same way by this common focus.

More specifically, both methods emphasize the utility of knowledge acquisition in the context of solving particular problems. Davis (1982) notes that having experts articulate their knowledge while solving actual problems is especially important when the performance program is designed to accommodate inexact knowledge in domains where knowledge has not been extensively formalized. In such domains, experts will often be required to formally codify pieces of knowledge for the first time. Allowing experts to articulate their knowledge as it relates to particular problems situates the knowledge acquisition process and makes the resulting knowledge base more robust.

### Verbal Protocol Analysis

#### Purpose

Verbal protocol analysis is a general term used to describe knowledge elicitation techniques in which a researcher, task analyst, or knowledge engineer interacts with an expert in order to document the expert's knowledge base and knowledge deployment during performance. While the verbal protocol approach is commonly used by knowledge engineers in the development of expert systems, the use of verbal data to study human performance has its roots in psychological

research studies of problem solving. Pioneers in developing the approach believed that only the richness of verbal data could adequately reflect the complexity of knowledge and the reasoning processes used by humans in complex problem solving tasks. (Newell & Simon, 1972; Ericsson & Simon, 1980).

The adaptation of verbal protocol methods to expert system development has consistently moved in the direction of prespecifying a given representation scheme for knowledge elicitation, the dominant one being condition-action rules; however, there is more flexibility in verbal protocol methods than one may expect. Further, the richness of the data captured in verbal protocols makes the approach particularly useful for studying domains in which expertise has not been extensively formalized or is ill structured.

#### Procedure/Result

Wielinga and Breuker (1985) describe five basic methods for eliciting verbal data. Since the methods complement each other with respect to the type of information they yield, a combination of these methods is typically used in any given application. In a focused interview, the expert answers questions from an agenda established by the analyst whose goal is to acquire an overview of the domain or task. The interview focuses on the domain, the functions of expertise, the job environment, and characteristics of the user of the prospective expert system. In focusing on general issues, the interview provides the basis for later, more detailed discussions in a structured interview. In a structured interview, the researcher probes the expert for detailed explanations of general concepts. Here, the purpose is to provide the researcher with deeper insight into the structure of domain concepts and their interrelationships through queries about the static aspects of the domain, including never-changing, indisputable facts, theories, and conceptual objects.

By contrast, the dynamic aspects of the domain are encountered through actual task performance, for example, the dynamic reasoning processes engaged in by experts during solution searches. These processes are more easily captured in introspective reports where the expert describes how hypothetical problems would be solved, and in self-reports in which the expert

thinks aloud as s/he actually solves problems under simulated conditions. Problem solving may also be observed during user dialogues where an expert answers the questions of a prospective user of the proposed knowledge base. Finally, the expert may be asked to review protocols obtained earlier to provide necessary elaborations and to fill in gaps in the data.

The richness of verbal protocol data arises from the relatively few constraints placed on the questions from the analyst or on the responses of the expert. This procedural looseness as well as other features of verbal protocol methods have not escaped criticism, however. The introspective nature of the data captured in verbal protocols has been criticized by researchers on several grounds (Nisbett & Wilson, 1977). First, because subjects cannot be assumed to have conscious access to the intermediate stages of processing, the verbal data they report during problem solving may not correspond to the actual internal representations they use. Secondly, verbal reporting during problem solving may artificially influence the form and content of the data by requiring subjects to verbalize events that would not normally be reported during task performance. Finally, because of the flexibility of language, different subjects may express the same thoughts in idiosyncratic ways, making the interpretation of verbal data difficult. Thus, introspective data have been seen by critics as useful only for generating hypotheses concerning the nature of psychological processes, but not for their verification.

#### Relationship to the PARI Approach

The PARI methodology produces the rich sort of verbal data needed to capture relevant knowledge and shed light on the processes used in certain types of problem solving. However, it incorporates several features designed to obviate the criticisms noted above. First, the data are collected in situ as subjects think aloud while they solve problems. Subjects are not asked to respond retrospectively to questions which can encourage them to speculate and draw inferences about their thought processes. Concurrent verbalization produces more detail in subjects' descriptions of their thoughts since what is remembered decreases with the delay in recall.

The PARI procedure also provides a structure for the interview which the researcher or analyst uses as a framework for probing subjects: for each step in the problem solution, the solver is asked to identify the action being taken at that step, the goal or cognitive precursor to the action, and after being told the result of the action, is asked to interpret the result. This structure was derived empirically from observation of dozens of technicians engaged in electronic fault isolation tasks (Means & Gott, 1988; Gott, 1987). These technicians' natural approach to troubleshooting is to take some action or series of actions based on an hypothesis about the fault location which is derived from some internalized mental representation of how the circuit works. Experts also deploy a strategy to investigate the circuit that will allow them to narrow down the problem space and then to interpret the outcomes of their actions in terms of current hypotheses and the appropriate next steps. Their use of mental models to construct solutions appears to be something that experts can readily talk about and represent in diagrams. Whether or not the data reflect all of the features of subjects' internal representations is not clear. However, it is our belief that the data captured in these studies yield multiple levels of description that are most useful for identifying instructional targets for teaching adaptive problem solving.

A second advantage of using a structured interview technique like the PARI procedure is that the data are collected systematically. Such a framework is particularly useful in large-scale research where many individuals may be collecting the data. The data are less likely to be influenced by inconsistencies in the task analyst(s)' approach to interviewing which can compound the complexity of the interpretation process. The structure of the interview also facilitates comparisons across subjects, problems, and domains, since the same basic questions are asked under all conditions.

### Summary

The PARI methodology borrows several features from the approaches to task analysis described in this section. Like the ISD approach, our method attempts to provide a practical, analytic tool that can be used by nonscientists for instructional development. It focuses, however, on the contribution of multiple types of tacit knowledge to task performance and the cognitive

processes that deploy the knowledge. Like the GOMS approach, the PARI procedure also attempts to capture the structure of a task and the reasons underlying a particular sequence of problem-solving steps. The strategic processes responsible for organizing the solution and for searching the knowledge base are critical components of the performance models being generated from cognitive task analyses. Providing executable performance models is the goal of a GOMS analysis and of knowledge engineering as well. The PARI methodology is consistent with this approach and acknowledges the importance of modelling performance at varying proficiency levels for the purpose of identifying instructional targets and learning trajectories. In order to capture the richness of technical knowledge and the full complexity of problem solving by human experts, a verbal protocol method was adopted for the PARI procedures. The following section describes the procedure in greater detail.

### III. THE PARI METHODOLOGY: DATA COLLECTION

In this section, we describe how PARI data are collected and discuss the relationship between this technique and the theoretical framework presented in Section I of this guide. The PARI methodology is a procedure for examining cognitive tasks that involve the interaction of a human problem solver with a complex system.<sup>5</sup> The procedure revolves around a structured interview during which problem solvers in the domain of interest are asked to think aloud while they solve authentic problems. The interview is structured to simulate the actual problem solving-task environment and to elicit the performer's knowledge of the system, problem solving procedures and operations, and strategic control processes, including planning, knowledge deployment, and performance regulation/monitoring (see Figure 1). The intent of this problem-situated approach is to reveal knowledge and skill in the context of their use; therefore, problem solvers are probed extensively to make explicit the reasons for the content and organization of their solutions. Once the reasons are made explicit, they become knowable by learners and concrete targets for training.

#### Overview of the PARI Procedures

##### Stages of the PARI Methodology

The PARI data collection procedures comprise nine stages, the first four of which are preparatory to the basic PARI structured interviews (see Table 4 ). In general, the first stages establish the sample of experts that will contribute to the task analysis and identify at a general level the problem solving tasks and associated cognitive skills that are to be considered as instructional targets. These tasks and skills serve as the initial foci in the development of specific problems to be solved during the PARI interviews. The final five stages of the procedure involve

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<sup>5</sup> Although the PARI methodology was developed in the context of studying electronic troubleshooting (which involves interacting with a technologically complex system), we believe the procedure can be generalized to the study of other types of human-system interactions.

the basic expert and novice interview sessions, the followup rehashes, and reviews of the data by experts.

Table 4

*Stages of PARI data collection procedures.*

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*Stage I:* Identification of experts and orientation of researchers

*Stage II:* Focus of training established

*Stage III:* Generation and consolidation of problem types

*Stage IV:* Problem category assignment and problem design

*Stage V:* Anticipation of PARI solution paths

*Stage VI:* Generation of expert solutions

*Stage VII:* Problem set review by expert problem solvers

*Stage VIII:* Generation of problem solutions by intermediate and novice technicians

*Stage IX:* Problem set review by independent (advanced) experts

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### The PARI Structure

The cornerstone of the methodology is an expert problem-solving dyad. One expert poses a problem and simulates equipment responses to a second expert, who attempts to (verbally) isolate the fault which has been conceived by the first expert. The dyad format is then extended by pairing intermediate and novice technicians with an expert who poses a problem and simulates equipment responses for each problem solver. During each interview, the role of the researcher/task analyst is to record the problem solver's solution steps as discrete operations or Actions, e.g., "trace schematic for XYZ circuit card" or "measure voltage at pin 28." Then the solver is probed by the analyst to express the reasons (or Precursors) for the actions. A Precursor reveals the particular goal or intent of the solver in executing each action; in turn, a sequence of precursors reveals the performer's top level plan or goal structure. This is the glue that bonds the detailed steps together. The analyst also probes the performer for an Interpretation of the system response that is provided by the expert who is posing the problem. Finally, the analyst asks the



problem solver to draw a block diagram level-sketch of the relevant equipment to illustrate each solution step. The resultant series of sketches reveals the evolving mental models of the equipment used by the performer to guide his/her movement through the problem space.

Sequences of mental events such as these are called PARI structures (Precursor [to Action] -- Action -- Result -- Interpretation). An example node from a PARI trace (i.e., a single solution step) is shown in Figure 3. After a basic trace is recorded, a series of "rehashes" is conducted by the researcher/analyst to verify and elaborate the solution trace. To complete the process, an independent set of experts reviews the problem set to judge its completeness and representativeness, and the expert participants themselves rate the criticality of the cognitive skills required to solve each problem. We turn now from this overview to examine each of the data collection stages in more detail. Our particular focus will be on the theoretical and empirical rationale for each stage.

#### **PRECURSOR**

I want to see if the LRU ID resistor is good.

#### **ACTION**

Remove the cable from J12 of the LRU and ohm out the path through the LRU from pin 68 to pin 128.

#### **RESULT**

The reading is 1.55 Mohms.

#### **INTERPRETATION**

The problem isn't in the LRU, it's in the test station or the test package.

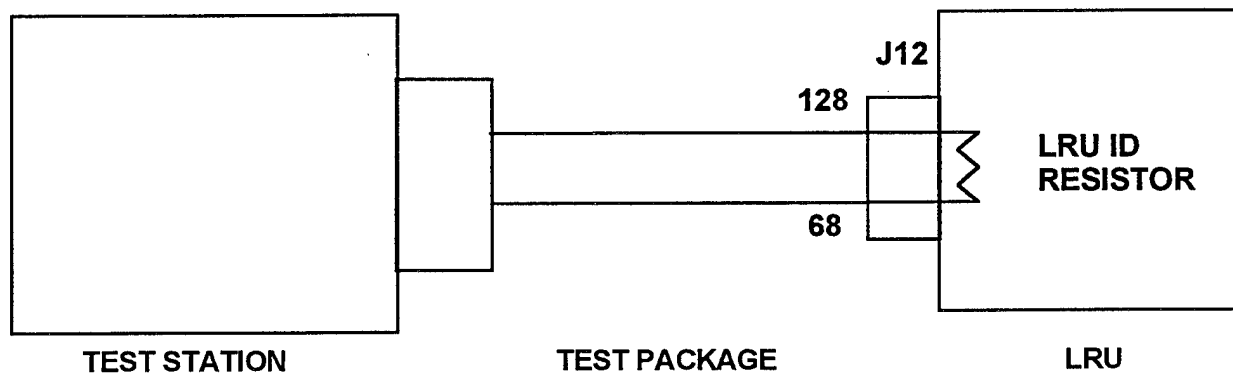


Figure 3. Single PARI solution step.

## Stage I: Identification of Experts and Orientation of Researchers

### Goal and Rationale

The identification of experts to participate in the PARI sessions involves several considerations that are central to the goals of the task analysis. First, the development of a cognitive model of skilled performance in a domain of ill-structured tasks requires input from multiple experts. The very nature of adaptive expertise entails the ability to consider a wide range of alternative solution strategies and associated procedures for implementing those strategies, based on one's knowledge of the system. Because different experts have different types and levels of system knowledge, as well as varying propensities to deploy different types of procedures, problem solving will vary from expert to expert. Any one expert may exhibit neither the full range of strategic and procedural options nor all of the device models that would inform a robust instructional system for complex problem solving.

In addition to providing multiple perspectives on problem solving, the expert participants must be sensitive to the training needs of novices in the field. Input from experts regarding the learning impediments of novices helps to determine the curriculum issues to be addressed by the training. Although some experts will have useful insights into training needs based on their own earlier experiences as trainees, it is beneficial if the selected individuals have had recent, direct responsibilities for training less-experienced personnel in an on-the-job training context. This experience can contribute to the validity of the training foci, which are established in Stage II, and to the problems that are developed in Stages III and IV as the foundation of the training.

The orientation phase of Stage I is intended to serve two purposes. First, it is designed to expand the researchers' domain knowledge so that the (fault isolation) problems that will be generated and solved in the later stages of the workshop can be reasonably well understood. Secondly, it provides an additional opportunity for the capabilities of the identified experts to be evaluated.

## Procedure

Procedurally, the first step in identifying expert participants (in our project) has been to have supervisors at a given work site select their best hands-on technicians for participation. The research team then interviews each technician to determine his/her ability to present technical information in a coherent manner, to convey technical information to a nontechnical audience, and to participate productively in the research effort. More specifically, each expert is asked to provide information about their personal training and work experience (see Appendix A for an illustrative example of a training and experience questionnaire), and is then interviewed about the equipment systems that are maintained in the job in question.

The orientation of researchers begins by having each expert generate a description of the equipment system that is the primary focus of her/his job. Experts are instructed to begin at a fairly general level of description and to draw illustrative block diagrams that show the components being described and their interrelationships. Increasingly detailed descriptions of the system are then elicited by having the expert iteratively analyze each component illustrated in the preceding description and draw any new components mentioned.<sup>6</sup> Once the expert has described the system in as much detail as possible, s/he is asked to talk about major physical and functional components of the system and their interactions. Finally, each expert is asked to discuss examples of typical problems (malfunctions) encountered with this system. This step is intended to prime the experts for discussions about representative equipment problems that would provide a solid basis for training.

The equipment orientation is concluded with a meeting at which the experts orient the researchers to the site-specific workplace ecology, that is, conditions and practices of the

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<sup>6</sup> An automobile analogy is used to illustrate how one might generate a description of a system at increasingly detailed levels of analysis: at the major functional component level, an automobile can be described as drive train, body, and frame. At a lower level, the drive train can be described as engine, transmission, axle assemblies, etc. At an even lower level, the engine can be described as pistons, cylinders, etc. One can proceed in this manner until the nuts and bolts level is reached, if desired.

workplace or requirements of the job that influence how the job is performed. A questionnaire relevant to the workplace ecology of the aircraft maintenance jobs studied under the BJS project is provided in Appendix B.

### Result of Stage I

Stage I is concluded when the research team makes a final selection of the experts to participate in the PARI workshop. It has been our experience that the quality of expertise needed to conduct an effective cognitive task analysis is quite rare. For example, in a technical work cadre of 25 to 30 individuals, we have found that generally only one or two workers meet our criteria. These bona fide experts have on average 8 to 10 years experience in the domain and are still actively engaged in hands-on problem solving, that is, they have not moved into management/administrative positions. We have found that the best PARI products result when the highest level expertise at a site is involved in the workshop, even when that means that only two experts per site (the minimum) participate and that the research team will have to travel to a second and even a third site to obtain input from a sufficient number of individuals (usually six to eight).

### Stage II: Focus of Training Established

#### Goal and Rational

One of the basic assumptions that underlies the PARI methodology is particularly salient for Stage II, namely, that results of the task analysis will be used to develop training that targets complex problem solving. The purpose of Stage II is to have the experts selected in Stage I identify the cognitively complex tasks within a job and specify the general nature of the associated cognitive demands. These instructional foci influence all subsequent task analysis activities.

## Procedure

In the study of Air Force job specialties, a good first step is to have experts examine the results of occupational surveys and Specialty Training Standards. These reports provide an inventory of the general duties and the more specific job tasks required by a technical specialty. They also provide information concerning the frequency with which tasks are performed as well as their level of difficulty (defined in terms of how long it takes, on the average, for a person to learn the task). For example, for aircraft maintenance jobs, the occupational surveys might list duties such as maintaining radar systems, maintaining optical sight or integrated display systems, maintaining low altitude radar altimeter (LARA), and so forth. Within those duty categories (the last one for example), tasks listed might include, "isolate malfunctions to LARA calibrator units," or "perform operational checks of LARA systems."

The task inventory and the associated frequency and difficulty ratings are used by the experts and research team to guide the identification of maintenance tasks that warrant a cognitive analysis, i.e., tasks that have sufficient cognitive complexity. Two related criteria are used in judging the cognitive complexity of tasks: the stability of the task (or system) environment in which problem solving occurs and the number of decisions required in performing the task. An unstable job environment is characterized by unpredictable events or conditions to which the problem solver must respond. By definition, an extremely complex system presents an unstable task environment because of the large number of possible malfunctions that may occur. Because it is difficult to anticipate all possible equipment conditions, it is correspondingly difficult to prespecify all possible sequences of solution steps. As a consequence, there are often no well-established procedures for task performance, and thus technicians are confronted with ill-structured problems. Even when established procedures exist, they might be inefficient or inadequate under slightly altered conditions.

The number and complexity of required decisions are in turn closely tied to the ill-structured nature of the task. Decisions may be numerous and/or complex because of the number of alternative choices available, because of the number of factors that must be considered in making

the decision, or because the relative importance of various factors changes with task conditions. For example, in troubleshooting aircraft systems, skilled technicians continuously consider the ratio of cost to benefit in deciding when and how to pursue a particular subgoal. The actions they elect to take are supported by a cost-benefit rationale wherein time, effort, and risk to the equipment and to themselves are minimized and information value and progress toward restored equipment functioning are maximized.

### Result of Stage II

Stage II is completed when a consensus has been reached on the cognitively complex tasks in the domain and a general characterization of the sources of the task-related learning and performance difficulties has been generated. Together, these tasks and associated cognitive demands provide the initial training foci for conducting Stages III and IV.

### Stage III: Generation and Consolidation of Problem (Fault) Types

#### Goal and Rationale

With the cognitively complex tasks and associated learning/performance difficulties from Stage II providing the focus, experts are directed in Stage III to generate an exhaustive list of the equipment malfunctions (and their causes) that can initiate task performance. The goal is to have experts independently generate and then collectively consolidate the instances of system causes and effects that are related to the tasks from Stage II. Experts then group related instances into meaningful fault (or problem) categories. This process can be illustrated with a car analogy.

A cognitively demanding task in automobile repair may be troubleshooting a fail in the car's electrical system. Presenting symptoms may be failure of the headlights to come on. The particular source(s) of equipment malfunction that would trigger that troubleshooting task might include a short in the headlight wiring, a bad fuse, a faulty dimmer switch, a faulty on-off switch, and so forth. These various causes of the manifested symptoms are related in a variety of ways,

one of which is the underlying device model (of the automobile subsystem) that a problem solver would invoke while reasoning about the fail. In the present example, a model of an electrical circuit that includes the concepts of wiring, circuit components, and switches would be required.

### Procedure

Stage III is conducted by having lists of fault instances generated independently by each expert and then combined and consolidated during dyadic and group discussion. Experts are instructed to specify fault instances in cause and effect language that will communicate a class of malfunctions as opposed to a very equipment-specific malfunction. For example, "bad stimulus routing caused by a stuck relay" would be preferred over "a stuck relay on the A8 card."

The consolidation of malfunction instances into defensible categories involves several steps. First, experts are asked to work in pairs, compare their independently generated lists, eliminate redundancies, and agree to a refined, consolidated list. Secondly, expert dyads are asked to group related faults on the refined list into meaningful categories. An organizing principle for the categorization is proposed: group instances together if they demand similar knowledge and skills for solution.

Several criteria are used to evaluate the resultant typology, which establishes the categories of problems to be generated in the following stages and used as the basis of training. First, a problem category should have face validity in the sense that experts would agree that this type of problem occurs with enough frequency that it is a worthy topic of training. Secondly, a problem category should have instructional value by virtue of exercising the cognitive skills, including equipment system knowledge, established as training foci in Stage II. In addition, each category should be illustrated by one or more example problems (causes and effects) to clearly communicate the nature of the category.

From a cognitive theory perspective, the problem typology that results from a consolidation and grouping of fault instances should reflect the disparate knowledge structures required for expertise in the job. In other words, a cognitive skills architecture (such as that shown in Figure

1) should be imposed on the domain of possible problems so that the typology covers a range of how-it-works, how-to-do-it, and how-to-decide-what-to-do-and-when knowledge. To illustrate, in the domain of airborne electronics (avionics), diagnosing problems involving radio versus lower-frequency signals requires knowledge specific to each type of signal since the signal characteristics have consequences for the types of cables used to carry the signals, the types of devices used to measure the signals, and so forth. A cognitive model of lower frequency signals would thus fail to include system knowledge and associated procedures that would have to be used to investigate a problem involving radio frequency signals.<sup>7</sup> Thus, problems involving both types of signals must be generated to represent the different equipment systems that employ each signal type.

### Result of Stage III

Stage III is completed when the refined, categorized, and exemplified fault lists from all pairs of experts are combined to yield the final problem typology. Appendix C shows an illustrative problem typology generated by a group of experts in an avionics job studied under the BJS program. The typology is used in the next stage to ensure that representative examples of all types of problems encountered in the real world will be generated as the instructional base.

### Stage IV: Problem Category Assignment and Specific Problem Design

#### Goal and Rationale

The problem typology (and exemplar problems) from Stage III is used to guide this stage, where the goal is to have experts design, in detail, representative problems that cover the

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<sup>7</sup> Notice that the strategy we use in Stage III to elicit representative causes of problems turns on the importance we ascribe to system knowledge in ill-structured problem solving. More specifically, our goal is to have experts specify instances of system malfunctioning, not instances of troubleshooting procedures. This strategy reflects our underlying theoretical position that technical expertise evolves from robust device models that can in turn generate needed procedural and strategic knowledge.



categories represented in the typology. These problems are then used during the problem-solving interviews in Stages V and VI.

### Procedure

Experts are matched or assigned to problem categories (from Stage III) according to their level of knowledge about the problem types or subsystems that the problems target. The illustrative (exemplar) problems generated in the previous stage may be further developed or different problems may be conceived to represent the categories in the typology. As part of designing problems, experts are instructed to (a) document conditions and consequences of the cause of the problem in a problem description, (b) generate problem statements that establish initial conditions and symptoms to present to other individuals who will be solving the problems, and (c) anticipate the supporting technical documentation (e.g., test procedures, schematics) that will be required by others during the solution process.

Experts are provided the following general guidelines for developing a problem for each of their assigned (or selected) categories: the problem should represent the problem category well by directly exercising critical skills and knowledge required for task and job performance; the problem should be intellectually (as opposed to physically) challenging, and thereby have instructional value as a learning activity; and the problem should be a good test of problem solving proficiency, that is, not solvable by some quick fix that averts major cognitive demands.

After a specific cause and effect are decided upon by the expert, s/he generates an overview or description of the problem. The problem description specifies the job, task, and equipment context of the problem; the category that the problem represents (from Stage III); the location of the fault in the system, i.e., the cause; the symptoms produced by the fault (effect); a diagram illustrating each of the above; and all anticipated technical documentation required to solve the problem. The problem description also indicates how the problem could be made easier or more difficult and describes the skills (e.g., signal tracing using schematics, taking ohm measurements, etc.) that are likely to be required in solving the problem.

Finally, a problem statement is written to describe the system conditions under which the problem would manifest itself and the symptoms that would be present in the real world were such a fail encountered. This problem statement is presented to individuals at the outset of the PARI interview during Stage VI. It is therefore a critical piece of the problem design because it initially establishes the authenticity of the problem context. The problem statement is accompanied by any other data related to the fail that the technician would have available in the real world, for example, the status of display panels, and which lights are illuminated, etc.

#### Result of Stage IV

Stage IV is completed when the experts have generated a problem description and a problem statement for each problem they have designed. Tables 5 and 6 provide a sample problem description and the corresponding problem statement, each containing the elements specified by the above procedure. The researcher should caution experts against disclosing to other research participants any information relating to the problems they have designed. This is necessary to ensure that experts will be naive with respect to the problems they will solve in Stage VI.

#### Stage V: Anticipation of PARI Solution Paths

##### Goal and Rationale

After designing a problem (Stage IV) but prior to presenting the problem to other experts to solve (Stage VI), the expert (problem designer) generates her/his own solution to the problem in a preparatory PARI interview. This interview is preparatory in the sense that the goal is to have the expert designer systematically work through possible solutions to her/his problem so that various solution paths can be anticipated prior to posing the problem to others. By anticipating alternative solutions, the designing expert is forced to think through what system responses (that is, Results) s/he will be required to give during PARI interviews with other performers. The preparatory interview also allows the researcher/task analyst to become familiar with the

Table 5

*Sample problem description.*

JOB: Electronic Warfare Test Station Specialist

PROBLEM CATEGORY: Connectors

CATEGORY EXEMPLAR: Pushed pin

**PROBLEM DESCRIPTION:**

The LRU-3 (Low Band Receiver Processor) is being tested. The ID resistor test (Test segment 11, measurement 1, test 1) fails. The task is to isolate the cause of the failure. The fault is a pushed pin at the back of the Interface Chassis drawer in connector J5. This pushed pin is on the path for making ohms checks from the DMM out toward LRU hookups. The fault diagnosis can be made easier or harder by moving the fault towards the LRU, or back into the test station toward the DMM, or possibly by making the pushed pin apparent by visual inspection or jiggling the connections.

**Anticipated skill requirements:**

- Visual inspections
- Swapping
- Reseating
- Jumpering
- Ohms measurements
- Voltage measurements
- Test control operation
- Test control interpretation
- Signal tracing

**The tech data needed to solve this problem include:**

- TO 12P3-2ALR56-78-1 (LRU flowchart, FIG. 5-10)
- TO 33D7-50-1-151 (Test package schematics, FIGS. 8-33, 8-23)
- TO 33D7-38-77-2-2 (Plugboard map, FIG. 4-15; CMG External connections, FIG. 4-40; MMX functional organization, FIG. 4-20)
- TO 33D7-38-77-2-3 (A/D console coaxial cable assemblies, FIG. 6-38; A/D interconnect diagram, FIG. 6-36)
- TO 33D7-38-77-28-1-1 (OAFI test summaries, TABLES 2-10, 2-11-2-13, 2-26; OAFI paragraph references, 2-37, 2-41, 2-45, 2-159)

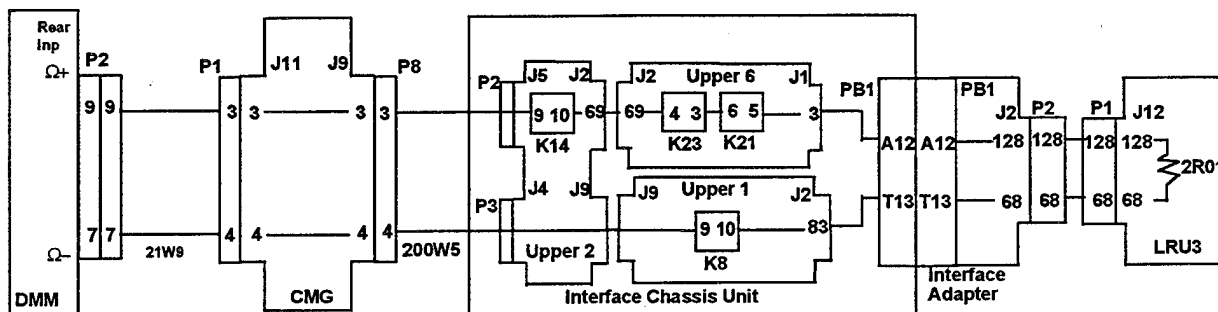


Table 6  
*Sample Problem Statement.*

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You are running a LRU-3 starting at test segment 10, entry point 1, the power check. On test segment 11, test 0, measurement 1, the CRT console shows a reading of 9.99999+37 ohms when performing a UUT identifier check. The CRT displays the following message:

P 141040 T0 S 11 D0 R24  
TSG 0 11

H 1 9.99999+37 OHMS 4.90364+02 4.03709+02 UUT IDENT

CHECK INTERFACE HARDWARE  
TEST PROGRAM, UUT P/N AND/OR REPLACE 2R01

END OF TEST

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details of the problem (i.e., which parts of the system are relevant to consider in the problem and which parts are not, how the problem affects relevant system components, how specific hypotheses might be confirmed or disconfirmed, and so forth). The analyst's familiarity with the problem enables her/him to ask informed questions in later stages when other individuals are attempting to solve the problem. The analyst's understanding of the problem greatly influences the accuracy and completeness of the PARI solution traces collected later.

Conceptually, the preparatory PARI interview is motivated by the same principles that influence the basic interview that occurs in later stages. Specifically, with the PARI approach, an empirically derived structure is imposed on the diagnostic problem solving process to elicit Actions, Precursors to Actions, Results, and Interpretations of Results. This structure assumes that a certain pattern of regularity exists in human reasoning about complex systems. The expected regularity is related to Clancey's (1986) assertion that system diagnosis is not simply the name of a disease, i.e., it is not a static product. Rather, it is a dynamic, self-improving argument. The evolving argument (diagnosis) systematically relates symptom manifestations to responsible agents in cause and effect terms. The PARI approach has been designed to capture the interactive steps by which hypotheses are declared, actions are taken to test hypotheses, symptoms are

observed as results, and results are related to an increasingly delimited set of responsible agents in cause and effect terms. In short, the PARI approach is intended to capture the evolving diagnostic argument in which symptoms are iteratively related to possible responsible agents. The mental (PARI) events themselves as well as the reasons behind the selecting and sequencing of the PARI solution steps are made explicit in the interview.

### PARI Interview Procedure

Overview. The interview unfolds according to the structure illustrated in Figure 4. In this figure, questions are attached to the interview elements to illustrate the probes that we have found to be the most effective for use by task analysts. These questions, combined with the PARI rehash questions (Figure 5), are designed to elicit instances of the multifaceted knowledge structures that are coordinated during complex problem solving. Appendix D provides an example of a PARI trace generated by an expert solving the problem described in Table 5. The trace contains both the PARI solution and the elaborative rehash data. Although the solution contains a large number of technical references, the interested reader will find the example helpful in clarifying both the structure of the PARI problem-solving sessions, and the nature of the resulting data.

Step 0. The interview begins as the expert considers the information given in the problem statement (context and symptoms) (see Table 6). S/he is probed by the analyst for an interpretation of the presenting symptoms. This initial step is considered Step 0 and contains only the Interpretation element of the PARI structure since the preceding Action and Result are already embedded in the problem statement. The expert is also asked to generate a sketch or (block-level) diagram to illustrate Step 0. The diagram should illustrate what is happening in the equipment as established by the problem statement and by inferences made by the expert from the symptom and contextual information that is initially provided in the problem statement. In general, the diagrams are very useful for depicting how the expert envisions system operation as the diagnostic argument unfolds. At step 0 the diagram is actually the expert's representation of

the problem. The expert's perspective on the system can be captured as s/he mentally parses the equipment into meaningful units. During the course of the interview, the diagrams should

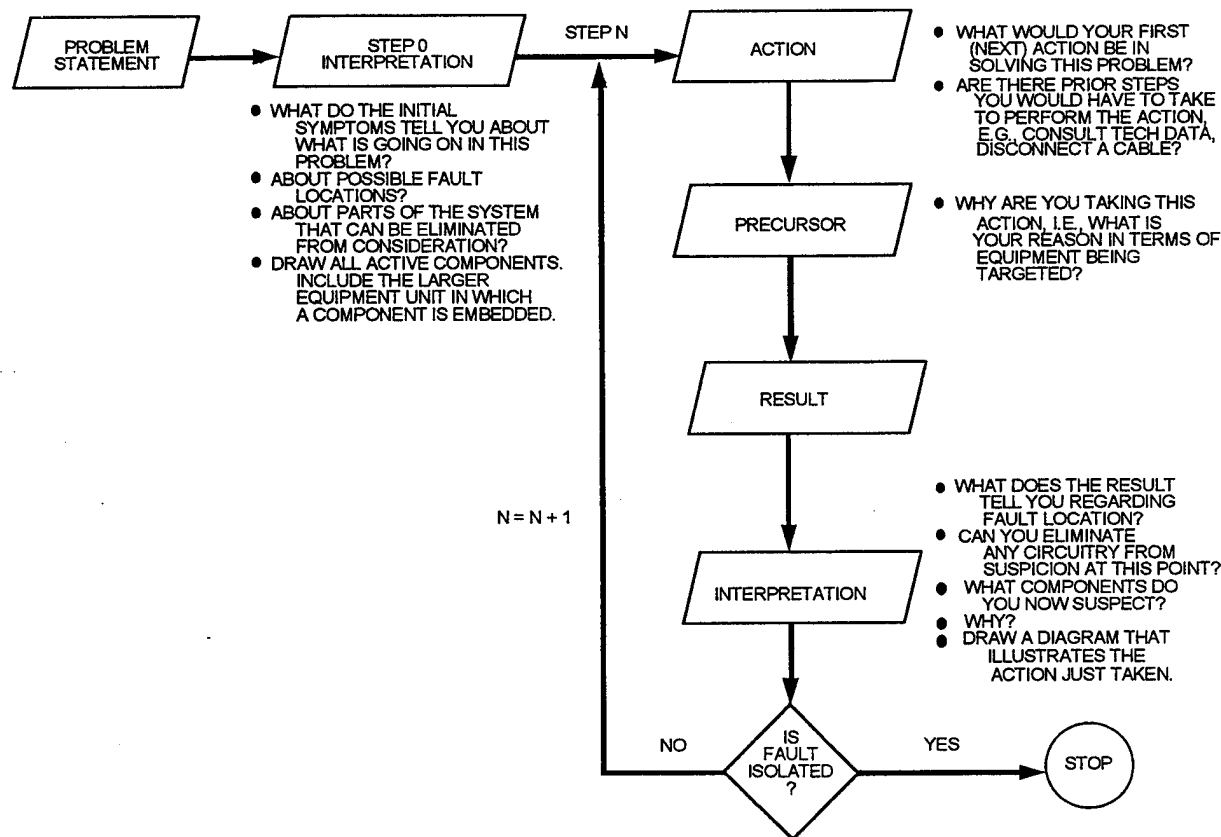


Figure 4. Problem solving sessions: PARI interview structure.

successively reveal the component(s) the expert targets as suspects and those which are eliminated or downgraded as suspects.

Later Steps. For each of the succeeding solution steps, the expert specifies an Action, the cognitive Precursor to the action, and an Interpretation of the Result. It is the researcher's responsibility to elicit from the solving expert a clear statement of each of these events as well as the supporting conceptual knowledge, or reasons behind the steps. This includes the diagrams representing the action taken at each step. The goal is to document the PARI structures at a level of detail that makes clear not only how the problem was solved but why it was solved in the particular way it was.

The elements of a PARI structure are as follows: an Action can be thought of as an operation that the human problem solver performs on the system (e.g., taking a measurement) or as an operation intended to collect information about the system (e.g., tracing schematics). In either case, the action yields a specific result and may constitute a test (or partial test) of an hypothesis. Associated with each action is a Precursor statement that describes the current hypothesis or the focus of the action (in terms of the system components that are being targeted), and how the action tests the hypothesis. In short, the precursor provides the justification or goal of the action. The expert also generates a diagram to illustrate system components that are relevant to each Action and Precursor at a particular step. Given that in the preparatory PARI interview the expert knows the location (or source) of the problem, s/he then provides the system's response to the action performed at that step (the Result), and produces an Interpretation of the result in terms of the hypothesis being pursued. The Interpretation should reveal what the Result tells the expert about the location (cause) of the fault, what system component(s) can be eliminated or downgraded as suspect causes, and what the expert now considers to be prime suspects and why. The step-by-step elicitation of these PARI elements is continued until the problem has been solved.

### PARI Rehash Procedures

Once the initial PARI trace has been recorded, the researcher conducts a series of "rehashes" (as part of the preparatory solution), wherein the expert verifies and elaborates the initial trace. Altogether there are five rehashes (see Figure 5). Exemplar rehash data are shown in Appendix D.

Rehash #1: Verification of the PARI trace. The purpose of Rehash #1 is simply to verify the solution trace by having the expert ensure that the analyst's documentation is accurate. The researcher reviews the transcript with the expert who clarifies any ambiguities and makes sure that the relevant diagrams are accurately drawn and labeled. This rehash gives the researcher the opportunity to ask for further explanations of any PARI elements that are not fully explicit in the

trace and to become better prepared for presenting the problem to other experts and less skilled performers.

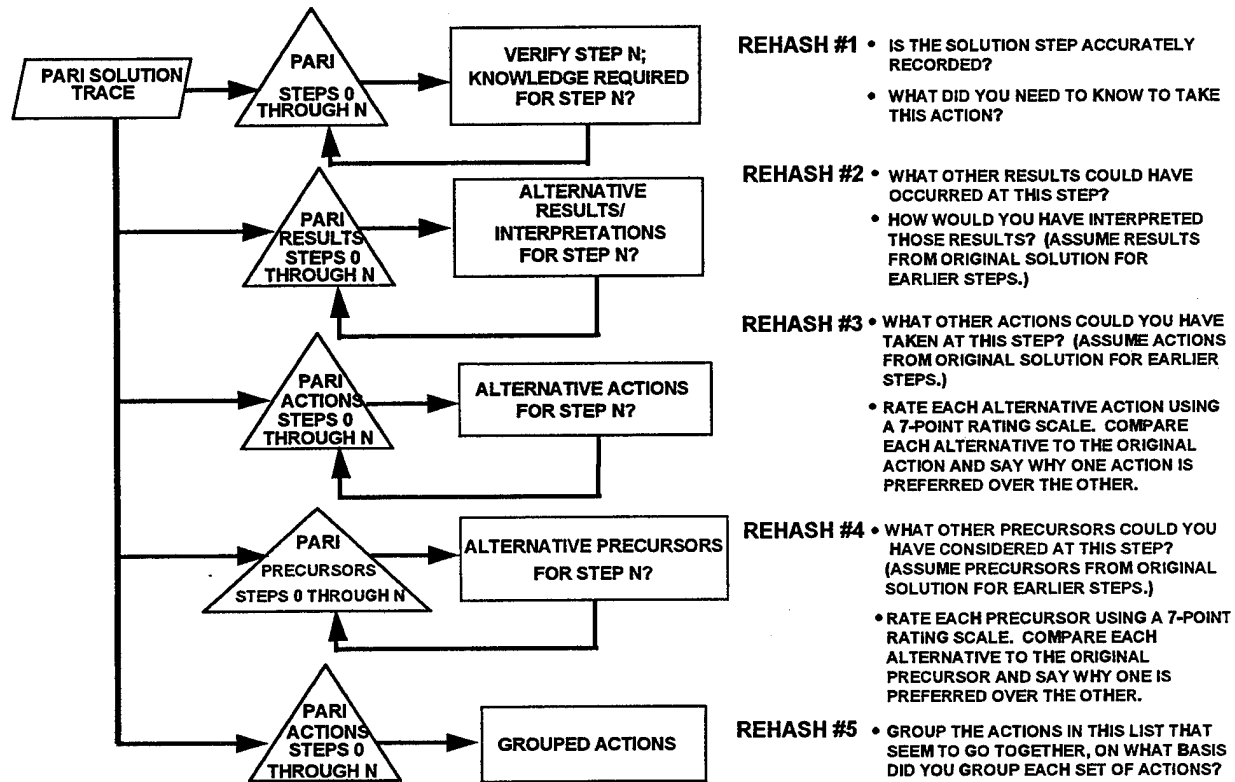


Figure 5. PARI rehash sessions.

The remaining rehashes are particularly instrumental in enhancing the cognitive model and its associated instructional power. The expert is probed to elicit alternative Results, Interpretations, Actions, and Precursors for each step in the solution and further to evaluate the merits of the viable alternative Actions and Precursors. In addition, the expert is asked to group the Action elements of the solution steps into meaningful clusters. The clusters reveal the problem solver's higher level plan or goal structure.

Rehash #2: Alternative Results/Interpretations. The second rehash is designed to elicit the full range of hypotheses being considered by the expert at each step. For each step in the solution, the problem solver is asked to state other possible outcomes of the action taken at that step, and to interpret each outcome. Each possible outcome (Result) will confirm or fail to



confirm some member of the hypothesis set. For example, suppose the original result of the Step shown in Figure 3 (an ohms measurement through the LRU ID resistor) was that a "good" signal was present (i.e., the proper resistance was being read). A reasonable Interpretation of that Result would be that there is good continuity through the resistor and therefore, that component is assumed good. Accordingly, the LRU containing the resistor is downgraded as a possible source of the problem and circuitry before and after the resistor is upgraded. Alternatively, an infinite resistance reading could be obtained (indicating discontinuity in the path through the resistor), in which case the above interpretation would be reversed. There are of course other details about the context of the problem such as which devices are operative in a particular test, the base failure rate of each operative device, and so forth that skilled technicians use to fine tune their Interpretations as well as their initial hypothesis set. Troubleshooting actions allow the expert to test empirically a range of hypotheses and subsequently to use results to mentally adjust the likelihood of each suspected cause.

Rehash #3: Alternative Actions. This rehash is designed to elicit and evaluate alternative procedures (or Actions) to investigate the equipment, given the targets (or goals) established in each Precursor from the original solution trace. As ill-structured problem solving, troubleshooting involves selecting a particular action or procedure from a range of possible procedures each time a step is formulated. In this rehash, the expert is asked to state all of the procedures (Actions) s/he would consider appropriate for pursuing the goal stated in the Precursor. For example, the Precursor (goal) might state "I want to see if component X on the circuit is good". One procedure (No. 1) might be to measure the output of component X, another (No. 2) to swap component X, and still another (No. 3) might be to determine (through a measurement) if component X is receiving the correct instructions from the computer to set up properly to process the incoming signal. Each possible procedure has specific costs and benefits associated with it that contribute to the underlying conceptual knowledge used by skilled troubleshooters in this kind of decision making. Eliciting the reasons behind the decisions is thus very important strategic knowledge for the PARI method to capture. In the above example, for instance, procedure No. 1 (measuring the output of component X) might be justified over the others because it yields more information and inflicts less damage (wear and tear) on the

equipment system than swapping. Further, if swapping is the selected action and it does not fix the problem, the solver cannot localize the fault to a smaller segment of the circuitry as is possible with procedure No. 1. Rehash #3 is concluded by having the expert use a seven-point rating scale (ranging from "much worse" to "much better") to compare each alternative procedure that s/he has generated to the original, selected procedure.

Rehash #4: Alternative Precursors. Rehash #4 is designed to elicit and evaluate alternative goals or Precursors considered by the expert in formulating his/her plan for investigating the equipment. As ill-structured problem solving, troubleshooting requires a continuous stream of decisions by the performer to determine what to do next based on system feedback (Results). This rehash is an attempt to make explicit the problem solver's reasons for focusing on one particular target (or equipment component) to the exclusion of other equipment targets. In this rehash, the expert is asked to state all equipment targets (Precursors) s/he would consider appropriate given the previously executed steps. For example, suppose the previous steps have reduced the suspicion surrounding component X (e.g., the LRU ID resistor shown in Figure 3.) Suppose further that the expert decides to target component Z (e.g., the test package) in the next step. Eliciting the reasons behind the decision to target component Z (to the exclusion of other possible targets) is also important strategic knowledge for the PARI method to capture. In the above example, for instance, targeting the test package over components within the test station might be justified, because that component is known to have a high rate of failure, or because previous steps have ruled out test station components. Rehash #4 is concluded by having the expert use the same seven-point rating scale used in the previous rehash to compare each alternative Precursor (equipment target) to his/her original selected Precursor.

Rehash #5: Grouped Actions. The final rehash is designed to elicit higher order groupings of actions for a given solution after the solution process is completed. By grouping actions, solutions can be analyzed at higher levels of abstraction where commonalities in problem solving across experts as well as across problems are most likely to become apparent. Procedurally, each expert is presented a list that contains the actions of the original solution trace s/he produced. The expert is then asked to group the actions that seem to go together and to explain the basis for

the resultant groupings. The groupings tend to reveal the larger chunks of the problem solver's plan for investigating the equipment and reflect the underlying device models of the equipment that give rise to the plan.

#### Result of Stage V

The result of Stage V is the set of solutions (one solution per problem) generated by the experts who developed the problems. In the next stage, experts present the problems they have developed to each of the other experts to solve.

In the discussion of Stage VI that follows, we examine the data produced by the problem solving interview/rehashes just described and explain how such data contribute to a cognitive model of performance to inform instruction.

#### Stage VI: Generation of Expert Solutions

##### Goal and Rational

As stated earlier, the cornerstone of the PARI method is the generation of problem solutions by experts who are naive to the source of the problem. In this stage, pairs of experts come together with the problems (and anticipated solutions) they developed independently in Stage V. In the larger data collection context, solutions are elicited from experts prior to conducting interviews with intermediate and novice technicians. There are several reasons for this sequence. First, the more expertise the problem solver has, the more predictable his actions are to another expert. The set of actions that must be anticipated by the problem poser is therefore rather constrained for expert PARI interviews. The experience of posing one's problem to a contemporary is nonetheless useful preparation for presenting the problem to less-skilled performers.

By conducting the initial interviews with experts, the researcher/analyst likewise gains valuable experience at the outset about problem solving from the most capable and articulate

performers. Less skilled performers may not be able to articulate the reasons for their actions or may even choose actions that have no logical basis. Cohesive PARI data are therefore more difficult to collect as skill level decreases, and this can cause confusion for the analyst who may have only minimal knowledge of the domain.

### Procedure

The PARI interview with expert dyads is conducted by the task analyst in much the same manner as described in Stage V; therefore, we give limited attention to the procedural aspects of Stage VI in this section. Instead, our emphasis is on how the various elements of the PARI structure inform a cognitive model of skilled performance, the building of which is the top-level goal of the cognitive task analysis. There are, nonetheless, several noteworthy procedural activities that are specific to this stage. They will be addressed first.

The first procedural feature of note concerns how the roles of the two experts are defined for this stage. Expert 1 poses the problem s/he has developed to Expert 2 by presenting the problem statement (from Stage V; see Table 6) and by giving Results to each Action taken by the second expert, or solver (Expert 2). The Results are stated as outcomes that would be achieved if the solver were actually performing the stated actions on the real equipment, vs verbally solving the problem in a PARI interview. Expert 1 (the problem poser) is directed to ensure that the information given to the problem solver as Results is as close as possible to the readings, features, and displays of the equipment operating in the real job environment. To illustrate the point, changes in display readings which would be immediately visible if the problem solver were interacting with the actual system might influence performance in the real job environment and should thus be provided as Results in the simulated PARI situation.

Expert 1 is also instructed to perform "reality checks" during the PARI interview by questioning any Actions of the problem solver that would not be normally taken in the real task environment. Similarly, the problem poser is directed to query Interpretations (of Results) by the solver that may be an artifact of the simulated PARI situation.

Expert 2 (the solver) is instructed to show normal shop behavior, to visualize the physical equipment in "the mind's eye" so that salient physical features of the equipment are noticed, and to think out loud, clearly stating troubleshooting Actions and surrounding events. The solver is also asked to sketch a block diagram to illustrate each step in the PARI sequence.

### Results of Stage VI

We turn now to an examination of how the PARI data inform the model of skilled problem solving described in Section I (see Figure 1). Multiple expert solutions to a variety of problems provide the primitive pieces of knowledge and reasoning processes that collectively constitute the experts' coordinated knowledge structures. We do not believe that the PARI procedure itself biases the data in favor of one performance model over another, that is, the PARI structure does not determine a priori the types of results that can be obtained. This assertion is supported by comparisons of PARI data obtained from experts to that obtained from less-skilled performers; the data reveal differences not only in the content and structure of their knowledge, but also in the coordination of different knowledge sources as well. In the following discussion, we rely heavily on our own data from avionics technicians to demonstrate the utility of the PARI procedure in modelling cognitive performances, both skilled and unskilled.

System Knowledge Structures. In the BJS cognitive skills architecture (Figure 1), knowledge of how the system works is assumed to be central to both procedural and strategic knowledge. System knowledge both drives strategic decisions and allows the problem solver to deploy, tailor, or infer appropriate procedures to use in efficiently investigating the equipment. Knowledge of equipment systems is captured in several ways by the PARI task analysis. First, experts' descriptions of the system which they generate during the equipment orientation phase of Stage I specify the content of the general system model possessed by the expert. During problem solving, pieces of this general system model are deployed and organized to form a series of device models that are specific to the problem being diagnosed. Each model is used as a basis for generating hypotheses concerning the problem source (or cause) as stated in the Precursors, and

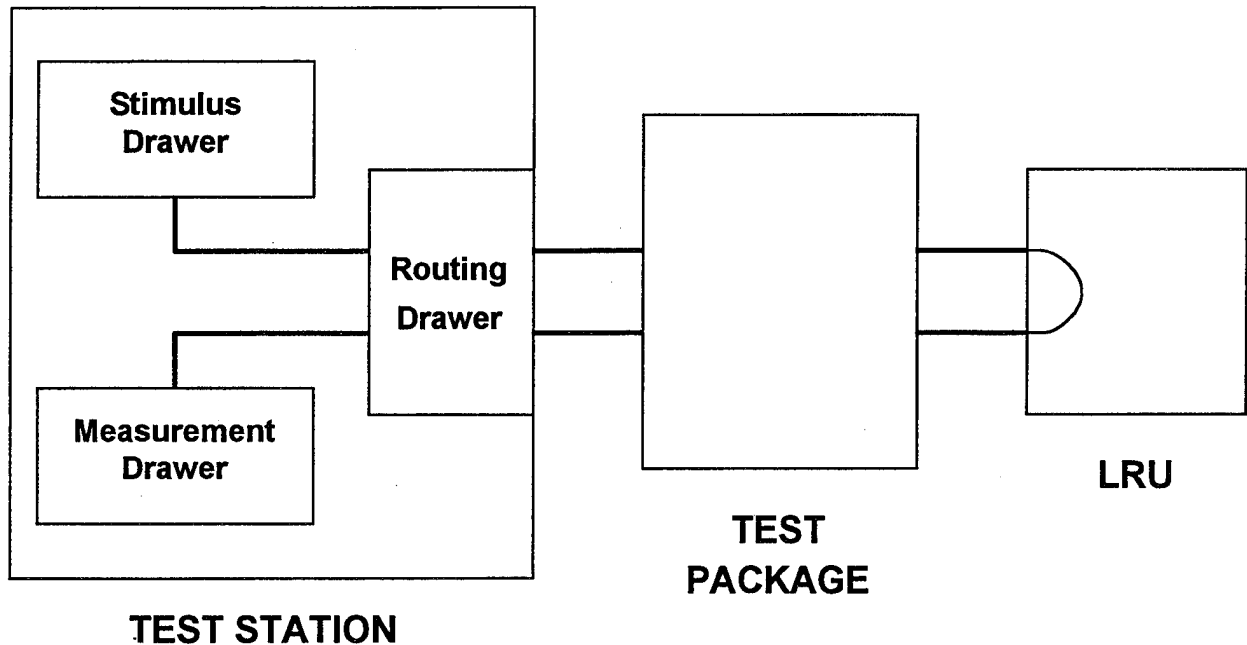
to construct tests of those hypotheses as specified in the Actions. At each step of the solution, the expert problem solver interprets the result in terms of the current device model and then updates the model to reflect new information.

The system knowledge that is accessed to form a problem-specific device model is primarily captured in PARI interviews via the diagram generated at each step of the solution and in the Interpretation element that integrates new information into the diagnostic argument. The diagram represents both an instantiation of general system knowledge and a special purpose representation of the device -- particularized to the symptoms and context of the problem. An example taken from an avionics expert's solution demonstrates how general system knowledge is used to generate specific device models. (The entire solution trace for this example and the associated diagrams and rehash data are contained in Appendix D.)

In this problem, a "test station" is being used to test a piece of jet equipment called an "LRU," or line replaceable unit. Figure 6 shows a diagram of the general equipment configuration during LRU testing. An LRU is a black box component that has been removed from the aircraft because of a suspected fault. It is connected to the test equipment, or test station, via a "test package" consisting of a cable and an adapter which serves as an interface between the LRU and the station. In testing an LRU, a stimulus device in the test station generates a signal which is sent to a routing device and then relayed to the LRU. The LRU generates a response to the stimulus which is then sent back to the routing device in the test station and relayed to a measurement device. In this example problem, the LRU is being tested with a computerized sequence of procedures when the test on the LRU identification resistor fails. The problem is to isolate the fault that caused this test to fail. Diagrams and PARI Interpretation elements reveal the system knowledge that is deployed in the fault isolation (problem solving) process, as described below.

Diagrams. Information in the problem statement is used by the expert to construct an initial (mental) representation of the problem, which is then depicted in a diagram produced after the

Step 0 Interpretation is made. The diagram and interpretation are in response to probes from the task analyst such as, "What is going on in this failed test? What do the symptoms tell you about



*Figure 6.* General equipment configuration during LRU testing.

the possible causes of the problem? What parts of the equipment will you initially target?" Figure 7 shows the Step 0 diagram produced by expert RK. Notice the close parallels between the general equipment diagram in Figure 6 and this specific diagram. Both diagrams incorporate the test station, test package and LRU; however, in the generic diagram (Figure 6), components within the test station are given generic labels, i.e., stimulus, measurement, and routing components. RK's Step 0 diagram provides labels to designate specifically the active components in this particular test, i.e., to illustrate what was going on when the particular fail occurred. In this test, both stimulus and measurement functions are performed by the digital multifunction meter (or DMM), and so that labeled component in Figure 7 serves both functions. The specific routing component here is the interface chassis. RK's problem-specific diagram also designates a particular LRU, "LRU-3", and a particular interface adapter, "LRU-3 I/A" (indicating that this adapter is used specifically in testing the LRU-3). The expert's Step 0 diagram thus constitutes an instantiation of a schema of the general equipment configuration.

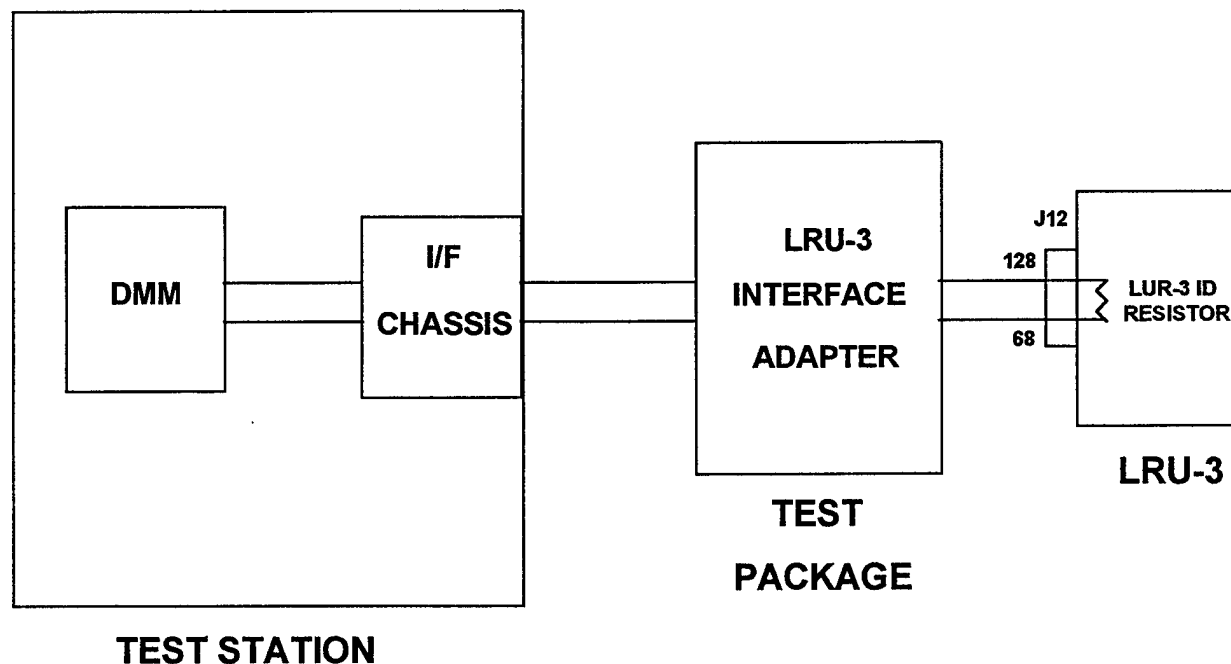


Figure 7. R.K.'s Step 0 diagram showing equipment configuration for a particular LRU test.

Interpretation Elements. System knowledge is also elicited during the Interpretations of PARI steps. Interestingly, the Interpretations reveal the close interplay between system (or how-it-works) knowledge and strategic (or how-to-decide-what-to-do-and-when) knowledge. To illustrate, the Step 0 Interpretation for the diagram depicted in Figure 7 included the following observations: "This test checks the LRU ID resistor, and the DMM (digital multifunction meter) is being used as the measurement device; I will initially focus on the LRU because the LRU ID resistor may actually be bad as the failed test indicates, or a pushed pin in the test package could have caused the fail; since a pushed pin is more likely than a bad ID resistor, the problem is more likely to be in the test package than in the LRU. I won't focus on the test station initially since troubleshooting the station is more difficult; I'll rule out the easier components first."

The strategic knowledge revealed here includes the following: the first decision was to identify the components of the system that were active when the test failed ("This test checks the LRU ID resistor and the DMM is used as the measurement device.") This decision significantly



constrains the equipment to be initially searched. Further, cost-benefit reasons are revealed that guide the sequencing of solution steps: "Since a pushed pin is more likely than a bad ID resistor, the problem is more likely to be in the test package than in the LRU. I won't focus on the test station initially since troubleshooting the station is more difficult; I'll rule out the easier components first." Notice that these reasons are tied directly to knowledge of the equipment system, thus requiring access to detailed knowledge of the general system.

The coordination of particularized system and strategic knowledge by this expert is further highlighted when compared with the types of Interpretations produced by novices. Due to impoverished system knowledge, novices appear to default to general or weak problem solving methods as strategy (e.g., find someone or something that will tell me what to do next). They show little capability to infer either a focus for their investigation or problem-specific diagnostic procedures from the system description provided in the problem statement.

#### Knowledge of Procedures and Operations

Using the same illustrative problem described above, we now consider how the PARI data yield information about the performer's knowledge of troubleshooting procedures/operations. Coordination between procedural knowledge and system knowledge is again the most salient finding in our own PARI studies. The instances of procedural know-how tend to be contained in all four PARI elements and the alternative actions.

Actions. Primarily, procedural knowledge is revealed in the Action statements of PARI solutions, as well as in the Alternative Actions that result from Rehash #3. When abstracted from the solutions of multiple experts, these Action instances can be grouped and made general to provide an inventory of the cognitive procedural skills required for task performance. Interestingly, in our work, experts and novices do not appear to differ substantially in their knowledge of troubleshooting procedures (e.g., taking measurements, swapping components,

checking connections, running computer diagnostics, etc.).<sup>8</sup> In most cases the novices we study have already acquired some procedural skills in their initial technical training prior to reporting to their first job assignment. This is not surprising since the execution of procedures is the most readily observable aspect of task performance and therefore represents an obvious target for training. However, despite some knowledge of procedures as the "tools of troubleshooting," novices generally possess these actions detached from their conditions of use. They may know how to execute a procedure but frequently fail to produce the specific variation of the procedure at the appropriate time. This deficiency is revealed in Precursor statements, where performers are probed for the reasons for their actions.

Precursors. What novices appear to be lacking is (strategic) knowledge that empowers them to select optimal procedures that enable meaningful progress during diagnoses. This conclusion is supported by an examination of the reasons that experts and novices give for their Actions as Precursors or goals being pursued. Whereas experts tend to select an Action driven by a goal that in effect represents a specific hypothesis about the malfunction, novices tend to be much less hypothesis driven. For example, an expert who elects to measure the path through the LRU that is active for the ID resistor test (see Figure 7) would be likely to provide as a supporting reason (i.e., Precursor or goal), "I'm taking this measurement because I want to eliminate the LRU as the source of the problem." It is important to note that the measurement procedure itself requires prerequisite procedural skills since the performer must be able to identify the test points from technical documentation as well as know what kind of measurement (ohms vs. AC voltage vs. DC voltage) is appropriate to test the stated hypothesis. This cluster of associated requirements is often daunting to novices. They typically have less-focused goals as hypotheses and only weak support for their actions. For example, a novice Action for this same problem may be to replace the ID resistor. The associated Precursor or reason may reflect no hypothesis at all and no expectations of the meaningfulness of the Result. Rather, the novice's Precursor is likely to be "I'm doing this because the computerized test tells me to swap the resistor as a remedial action." Rather than identifying the information they need (or specifying an

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<sup>8</sup> The notable differences concern the well-tuned or strong procedures displayed by experts versus the general, domain independent, or weak procedures often employed by novices.

hypothesis) and then selecting a procedure that will serve that goal, novices often choose procedures based on instructions from an outside source, or because they think the procedure might provide some useful information. They are often uncertain about what they expect to learn, however.

It should be noted that novices' reliance on procedures provided by an external source is not necessarily maladaptive or ill advised. The external support can provide scaffolding that assists learning as long as the reasons behind the procedures/decisions are made clear in the external information source. Further, if executing prescribed procedures gives novices valid experiences interacting with the system and observing its behavior, then these experiences become the basis for developing a general model of how the system works. Providing reasons for the procedures always enriches those learning experiences.

Results/Interpretations. Knowledge of problem solving procedures is also revealed in the performer's Interpretation of the Result of the procedure (Action). Without well-developed knowledge of how a procedure can be used to investigate the equipment, erroneous Interpretations of Results can be made. This phenomenon can be illustrated by an example taken from two solutions to the problem described earlier. (The reader may refer to Figure 7 which shows the equipment component targeted by the action taken in this example.) In this problem, both an expert and a novice chose to investigate the test package by running computer diagnostics on it. Each technician was told, as the Result, that the voltage checks passed while the ohms checks failed. The novice interpreted the failed ohms checks to mean that the test package was bad. He reasoned that since the purpose of a diagnostic program is to detect malfunctions in the test package, the ohms checks must have failed because of bad components in the test package. This, however, was not the source of the problem. The novice's failure to understand how the test package was tested and the role of other test station components in running the diagnostics led him to the erroneous conclusion that the test package was bad.

By contrast, expert RK's Interpretation of this result revealed inferences that were clearly based on his knowledge of how the test package diagnostic procedure works and how the

components of the equipment are interconnected. His Precursor stated that this procedure checks the internal circuitry of the interface adapter and that he thought this circuitry consisted of straight wires through the interface. When all of the ohms checks failed, he correctly concluded that the problem was in the test station "because there is no circuitry in the test package that is common to all of the ohms checks." He knew that these ohms checks were simply a series of continuity checks through individual wires in the interface adapter and that the likelihood of multiple broken wires was low. In short, he understood how the procedures worked and what conclusions to draw from its possible Results. The more probable cause was a failure in the test station that produced the observed effect in the test package diagnostic procedure. The importance of a well-integrated device model is clearly integral to mindfully using and interpreting procedures, as illustrated in this example.

These illustrative data support the view that knowing how to execute basic procedures is insufficient for skilled diagnosis and fails to discriminate between expert and novice problem solvers. While the procedure employed by both expert and novice was identical, their reasons for using that procedure and especially their interpretations of its outcome were the distinguishing characteristics of the two performances. The PARI procedure captured the telling details surrounding the use of the procedure, including critical performance components such as system and strategic knowledge.

Strategic Knowledge. While the presence of the final cognitive skill --strategic knowledge-- has been noted in our earlier treatments of PARI data, it is appropriate to conclude this major section with a discussion of how strategic decision making is elicited in PARI interviews. First, the overall plan or goal structure of the solution is captured in the groupings of actions obtained in the fifth rehash. In addition, the selection and sequencing of solution steps is at the core of ill-structured problem solving and thus strategic decisions can be accurately regarded as the glue of the solution process. The nature of those decisions is perhaps best revealed in the three rehash sessions where performers are asked to produce and evaluate alternative Actions, Precursors, and Results/Interpretations. For example, when selecting a Precursor or Action, the expert considers the amount of information that will be gained to further constrain the problem space and make

progress toward restoring equipment functioning. The selection of Precursors and Actions is therefore fundamentally tied to the expert's anticipation of alternative Results and the benefit ascribed to achieving those Results. Major factors considered by the expert in strategic decision making include costs such as mental and physical effort, time, danger, and equipment replacement costs. Benefits to be optimized include constraining the possible sources of malfunction and making progress toward restored equipment functioning.

Alternative Actions and Precursors. Knowledge of strategic decisions is captured in alternative precursors and alternative actions rehashes (Rehashes 3 and 4). Unlike novices, experts have multiple ways of approaching problems which allow them to choose among alternative equipment targets (Precursors) and alternative investigatory procedures (Actions). Both the contextual surround of the problem and information gained at previous solution steps influence the selection process. In Rehash 3, alternative actions are elicited from experts to make explicit the range of procedures considered appropriate to achieve a particular goal. The procedural options being considered by the problem solver are thereby revealed. Similarly, in Rehash 4, alternative precursors are elicited to establish the viable equipment targets considered as goals for investigation.

For example, in the problem described earlier, a technician might have several procedures (actions) available to determine whether the LRU ID resistor is bad. S/he may check for continuity through the resistor by taking an ohms measurement, replace the resistor, or swap the LRU and then rerun the failed test to see if the problem has been fixed. Similarly, in later stages of problem solving, the expert may have narrowed down the suspect causes to several component devices within the test station. S/he may target the measurement device, the routing device, or even the computer that provides input to the other station components.

After listing the alternative Actions and Precursors in rehash sessions, experts are asked to compare the original, selected Precursor and Action to the listed alternatives in an informal "cost-benefit analysis." The relative merits of each option are weighed by the problem solver who explains the reasons why one Precursor or Action should or should not be chosen over others.

We noted earlier that in the avionics diagnosis domain, these decisions appear to be based on a strategy that attempts to maximize the information gained at a particular solution step while minimizing the physical effort, mental effort, time, danger, and cost associated with carrying out that step. For any given strategic decision, estimates of these factors in turn depend on the individual problem solver's knowledge of the system. Because system knowledge varies across technicians, their decisions concerning the most efficient steps to take also vary. One expert may choose to investigate a component by measuring its output while a second expert may choose to run computer diagnostics on it; although the latter procedure might require less physical effort, it might also require more mental effort if the technician lacks the system knowledge needed to determine what the diagnostics are doing and to interpret the Results correctly. The weight given to these factors by a single expert may also vary across situations. In each situation, the expert must identify the tradeoffs among the various alternatives available in order to make a good decision. However, by requiring technicians to explain what makes one alternative better or more efficient than another in each specific context, the cost-benefit analysis captures what is common to the decisions of multiple experts (i.e., the factors that underlie these decisions in general) as well as what is unique about them.

Alternative Results and Interpretations. Strategic knowledge is also revealed when experts are asked to specify alternative results that may have occurred in response to a selected Action and to explain how such an outcome would have been interpreted. Again the expert's system knowledge is the determining factor in the quality of strategic Interpretations. By providing a means for mentally simulating the behavior of the system, a robust device model allows the expert to anticipate a procedure's possible outcomes. In turn, an examination of the set of possible Results and their Interpretations reveals how the expert distinguishes empirically between multiple hypotheses concerning the source of the problem.

For example, checking a signal at a certain point along the signal path might yield one of two results: the signal is either present or absent. While a present signal indicates that the fault is located downstream, i.e., past the point at which the signal was measured, an absent signal

isolates the problem to the circuitry upstream, or before the measurement point. This "split-half" strategy enables the technician to eliminate a large portion of the signal path from further consideration, but does not allow her or him to determine whether or not the fault is located in any one component. Swapping, on the other hand, will allow such a determination to be made, but is usually cost effective only when the fault has been isolated with a high degree of confidence to the component to be swapped. Procedures are thus strategically chosen by the expert to allow particular kinds of inferences to be drawn from expected results. These inferences are enabled via an internalized device model and are articulated in the Interpretation element and the alternative Result/Interpretation rehash.

Grouped Actions. Whereas the second, third, and forth rehashes (alternative Actions, Precursors, and Results/Interpretations) capture strategic decisions at a fairly local level, the grouping of actions reflects the overall goal structure of the solution and thus captures more global strategies. In generating these groupings, the problem solver is free to group actions on whatever basis s/he feels makes sense. For example, actions may be grouped in terms of the larger functional unit being investigated in a set of actions, or in terms the strategic goal being pursued. In general, however, we have found in our studies of avionics technicians that these groupings are closely related to the technician's device model as depicted in the Step 0 diagram.

For instance, in expert R.K.'s solution to the problem described earlier (provided in Appendix D), actions are grouped in terms of (a) ruling out the LRU, (b) ruling out the test package, (c) correlating the results of multiple tests (to narrow down the targets for investigation within the test station), (d) space splitting (within the test station), (e) checking the instrument select relays (the routing drawer, or interface chassis circuitry not previously eliminated) and (f) checking the path from the interface chassis to the DMM. R.K.'s step 0 diagram depicts the functional units of the equipment that were reflected in these goals: the LRU in goal a; the test package in goal b; the interface chassis in goal e; and the path to the DMM in goal f. The groupings also reflect strategic goals: ruling out components external to the test station first (goals a and b); correlating the results of multiple tests (goal c); and space splitting (goal d). Thus we find that the device model deployed to represent a particular problem drives the overall goal

structure of the solution and provides the basis for high level strategic decisions. The ability to accurately represent the problem and bring relevant facts to bear on its solution depends on the flexibility, and thus, the depth and quality of the system knowledge base.

### Stage VII: Problem Set Review by Expert Problem Solvers

#### Goal and Rational

In this stage, the goal is to obtain judgments on the goodness of the problem set from the experts who participated in the PARI workshop. This provides an opportunity for the experts to judge on the basis of the problem solutions they have seen whether the problem set adequately tests the cognitive skills and knowledge required for expert performance.

#### Procedure

Experts are asked to judge whether the PARI problems constitute a representative sample of those problems seen in the actual job environment, whether the PARI problems adequately "exercise" the skills and knowledge required for skilled job performance, and whether the problems have strong training utility. The experts are also asked to rank order the problems on level of difficulty for both expert and novice performers and to rate the criticality of the cognitive skills required for problem solutions. Experts are asked to rate each identified cognitive skill on three dimensions: usefulness of the skill in problem solution and in overall job performance, learning difficulty associated with each skill, and recommended training emphasis. Appendix E is a Problem Set Review Questionnaire used in BJS studies of Avionics job specialties.

#### Result of Stage VII

The feedback obtained at this stage is used for multiple purposes. First, judgments about the goodness of the problem set guide the researcher in determining whether additional problems should be generated in order to form a sound instructional base. Because an instructional



assumption underlying our program is that expert problem solving is the instructional target, it is important that the PARI problems as a group require a representative set of expert skills for solution. Secondly, judgments regarding problem difficulty and skill criticality are useful in informing both later PARI interviews with less skilled performers and to give focus and order to the later instructional design process.

### Stage VIII: Generation of Problem Solutions by Intermediate and Novice Technicians

#### Goal and Rationale

Collecting PARI solutions from less-experienced technicians is, in most respects, identical to collecting data from experts (see Stages V & VI). The primary difference is that rehashes are restricted to the first two, namely, the verification rehash and the alternative results/interpretation rehash. In our experience, it is difficult for less-experienced technicians to provide alternative precursors and actions because they require the articulation of alternative hypotheses and test procedures for each step in the solution. Generally, less-skilled performers lack such a range of procedural options and equipment hypotheses. Therefore, frustration occurs when they are unable to answer rehash questions. We have thus eliminated later rehashes during novice interviews to reduce the potential for frustration and because we have found this type of data from less-experienced personnel to be uneven and uninformative.

We have also adopted a practice of presenting problems to novices in order of increasing difficulty, based on experts' earlier rankings of problem difficulty (for novices). The goal is again to minimize novices' frustration and maximize the quality of the data by increasing the likelihood of early success in the PARI problem-solving sessions.

## Procedure

Procedurally, there is one issue that is unique to PARI data collection with less-skilled personnel, and that concerns how to continue the PARI interview if the problem solver seems to have hit a dead end. Since our purpose in conducting interviews with less-skilled performers is not to see how many problems they can solve independently, but instead to capture the content of their domain knowledge, our practice has been to provide assistance to compensate for gaps in their knowledge. The expectation is that such help will bridge to additional knowledge that can be revealed. More generally, our goal is to develop cognitive models that characterize the knowledge structures of less-skilled individuals (at their particular stage of development) so that instructional decisions such as learning trajectories, curriculum sequencing, and so forth can be better informed. Having less mature cognitive models to contrast with expert models in effect highlights salient skill differences that can be very important pedagogically.

Toward that end, we have adopted the practice of allowing the expert who is posing the problem to give structured assistance to the solver when s/he appears to be no longer making progress toward a solution. This practice assumes, of course, that dead-end situations can be defined explicitly enough to be recognized when they occur and that principled procedures for giving assistance can be developed. For our purposes, dead-end situations are those in which a sequence of actions (defined as  $x$  number of solution steps) is taken without deriving information that is relevant to the problem's solution. For example, in the avionics domain, a dead-end can occur when the problem solver takes a series of steps to investigate component(s) that are not on the active circuit path, when the technician continues to investigate a component that has already been eliminated as the source of the problem, or when the technician explicitly states that s/he does not know what to do next. Errors such as misinterpreting a result or choosing a procedure that does not test the stated hypothesis can lead to dead-end situations as well, but before any help is given, the technician is given several steps to self-correct.

In order to provide help in a principled way, we have developed several types of hints to guide the expert's determination of what information to give a problem solver when a dead-end

situation as defined above has been detected. The hint structure assumes that a barrier or dead end has been encountered at the beginning of a solution step, i.e., that the prior step has been completed. The first type of hint given in this situation is simply a review of all previous steps. Often a problem solver simply loses his/her place and forgets that some component has already been tested and found good. As a consequence, a recapitulation may get her/him back on a viable solution path. If the technician is still having problems determining what to do, the next type of hint is a suggestion concerning which component might be targeted for investigation that is, a Precursor is suggested. Having been told what to investigate, the technician may still not be able to state an action that would test that component, in which case, an appropriate Action is suggested by the expert. If the technician is unable to correctly interpret the result of the suggested action, the expert interprets it for him. The hint structure thus corresponds to the PARI elements of one solution step (Precursor, Action, Result, and Interpretation). If the problem solver cannot continue independently after this kind of assistance on one step, it is assumed that the technician's knowledge related to this problem has been exhausted and the interview is ended.

#### Stage IX: Problem Set Review by Independent (Advanced) Experts

The purpose of the final stage, Stage IX, is to have the problem set evaluated by senior experts who have a broader experience base than those who actually participated in the PARI workshop. These individuals are generally in management positions where they no longer work on the equipment systems being studied. However, because of their experience at a variety of job sites, they are in a position to identify whether there are site-specific conditions that have inappropriately influenced the problems contained in the problem set. Also, they are asked to review the accuracy of the problem and evaluate each problem's representativeness, completeness and utility in training. Appendix F contains a questionnaire designed for this purpose in studies conducted under the BJS program. This final evaluation provides an independent estimate of the goodness of the problem set based on the criteria previously used in generating the problems.

## Summary

The preceding description of the PARI data collection procedures emphasizes several themes that provide the basis for the method's design. One recurrent theme is that the cognitive processes and structures used in solving problems are best revealed in **dyadic interaction** during a **situated problem-solving** task. Thus, experts are asked to generate and solve realistic problems in a setting that simulates the actual task conditions. Second, by imposing a **structure on problem solutions**, data are collected systematically, ensuring that the knowledge underlying a problem's solution is made explicit as well as the observable, behavioral solution steps. Establishing the reasons that drive particular solution steps reveals important instructional targets that would not be captured if these reasons were not systematically accessed or probed. Third, in knowledge-rich domains, there is no "preferred solution" to any given problem (i.e. one that all experts agree on) since the content and organization of experts' knowledge differ. Thus, the PARI methodology acknowledges the importance of input from **multiple experts**. Finally, ill-structured problem solving is characterized by instability in the task environment which means that no single solution method is appropriate for solving all problems under all conditions. To establish the conditions under which different problem-solving approaches are appropriate, and what influences the selection of a problem-solving strategy, solutions to a **representative sample of problems** are required.

#### IV. UTILITY OF COGNITIVE MODELS

In this section we examine the application of the PARI methodology as a knowledge representation tool to aid instructional development and skill assessment. The utility of PARI-generated cognitive models in practice-centered instruction is actually tied to the nature of the targeted skills. Proficiency in modern work environments often requires the coordination of multiple types and levels of knowledge under diverse conditions to pursue various interrelated goals. As a result, the coupling of knowledge to goals occurs at a variety of levels for skilled performers, suggesting that to be effective, instruction needs to be informed at comparable levels of specificity and abstraction. Cognitive models can provide the necessary detailed representations, as well as reveal the mechanisms (strategies) for selecting and activating the appropriate knowledge. The models can ensure that the interrelated cognitive components that constitute skilled performance are treated instructionally and that the forms and levels of knowledge targeted by instruction can meet the demands imposed by actual performance contexts.

The PARI methodology has also proven useful in evaluating training developed from PARI-based cognitive models. Since PARI problem solving sessions are situated in realistic conditions that simulate the task environment of the actual job, the procedure serves as a practical assessment tool, yielding valid measures of technical skill. Performance data of individuals of unknown proficiency can be evaluated against the models which in turn, are based on the performance of individuals at known levels of proficiency. Thus, the PARI methodology underlies both the ability to model or define the criterion performance, and the ability to evaluate the extent to which an individual has reached the criterion performance level.

There are at present three training studies associated with the Air Force BJS program that provide illustrative examples of the use of cognitive models from PARI data to inform instruction and skill assessment. Before describing those studies, we will quickly review the principles underlying the PARI procedures.

In Section I of this paper we described the purpose of the BJS program to develop an integrated skill analysis/instructional development technology that promotes both depth and breadth of proficiency in the maintenance of highly complex systems. The increasing sophistication of equipment systems used in virtually every technical job environment often requires a deep understanding of equipment functionality to successfully perform complex diagnostic tasks. Second, the variety of equipment systems used by a worker throughout a career requires adaptiveness, such that mastering the functioning of one system should foster accelerated mastery of other systems. Developing training that promotes both deep and broad system understanding is critically dependent on a methodology that (1) allows the criterion performance (i.e., the skilled, adaptive performance of the expert) to be modelled in detail, and (2) that facilitates comparative analyses of performance models across domains as well as across differing levels of proficiency. As a knowledge representation tool, the PARI methodology has been developed to respond to our needs to characterize both the depth and breadth of technical expertise. Further, the procedures have been codified for use by nonscientific personnel.

The following description of training studies illustrate in general how the output of a PARI analysis is used to build an instructional framework and ultimately, curriculum content and method.

### PARI-Based Training Studies

#### Proof-of-Principle Study

Rationale. An early training study was conducted to evaluate the use of performance models derived from PARI data as the basis of instruction (Gott and Pokorny, 1987). In this study, the general approach was to identify differences in the cognitive performance models (PARI data) for expert, intermediate, and novice avionics troubleshooters and to design a training intervention based on these models. The expert performance models provided the distal goals of the training, but more importantly (for this short-term undertaking) the less-than-expert performance models provided the basis for proximal performance goals, thereby informing

instructional sequencing. Collectively, models of successive approximations of expertise provided a learning trajectory as a skeletal instructional framework. This trajectory enabled us to determine whether the training intervention was effective in moving novice technicians toward more expert-like troubleshooting performance.

Development of Cognitive Models. PARI data were collected from a range of F-15 avionics maintenance personnel so that expert, intermediate and novice performance levels could be specified. Cognitive models were developed by extracting from all PARI traces instances of Precursors and Actions, including system diagrams and supporting reasons, and then classifying instances into appropriate cognitive skill categories. For example, grouped Action instances yielded procedural categories such as "visual inspections", "swapping", "measurement taking", and "computer control/software interpretation." Grouped instances of Precursors yielded goal structure categories such as "verify fail," "expand information on probable cause of fail," "test suspected component's inputs/outputs to locate probable cause of fail." Table 7 provides examples of Action and Precursor instances extracted from the PARI data, along with the categories to which they were assigned.

Table 7  
*Grouping and classification of actions and precursors.*

<u>ACTION INSTANCE</u>	<u>PROCEDURAL CATEGORY</u>	<u>PRECURSOR INSTANCE</u>	<u>GOAL STRUCTURE CATEGORY</u>
<ul style="list-style-type: none"> <li>• Check pins on test package</li> <li>• Check fault indicator light</li> </ul>	Visual Inspections	<ul style="list-style-type: none"> <li>• Want to verify 5V power supply fail not a fluke</li> <li>• Want to verify failed diagnostic not a fluke</li> </ul>	Verify Fail
<ul style="list-style-type: none"> <li>• Swap Threat Simulator A5 card</li> <li>• Swap card N4A1 with like N4A3 card</li> </ul>	Swapping	<ul style="list-style-type: none"> <li>• Need more information on drawer serviceability</li> <li>• Need more information on resources used in failed test</li> <li>• Want to trace stimulus input to get complete routing</li> </ul>	Expand Information on Probable Cause of Failure and its Inputs/Outputs
<ul style="list-style-type: none"> <li>• Run diagnostics on high frequency measurement card &amp; coax switch</li> <li>• Run diagnostics with bit dump</li> </ul>	Computer Control/ Software Interpretation		
<ul style="list-style-type: none"> <li>• Test for good signal out- out of TP4 with oscilloscope</li> <li>• Ohms check between J110 and J4 with digital multimeter (DMM)</li> <li>• Put N4A1 on extender and test for 18VDC with DMM</li> </ul>	Measurement Taking	<ul style="list-style-type: none"> <li>• Want to test most likely suspect on stimulus path</li> <li>• Want to check other cards in signal flow path</li> <li>• Want to check for good input signal at N4A1</li> <li>• Want to check wiring between source of signal (N3A16) and N4A1</li> </ul>	Test Inputs/Outputs to Probable Cause of Failure

The procedural categories, e.g., measurement taking, led to fine-grained explications of the procedure in a narrative writeup called a skill definition. Skill definitions make procedural skills clear enough for teaching and testing purposes by providing an analysis of the step-by-step subcomponents of the skill and the conditions under which the skill is activated. The coordination of the procedural skill with system and strategic knowledge is also defined. For example, informed decisions in selecting among procedures such as visual inspection, swapping, measurement taking, or using computer diagnostics depend on the current goal and require an evaluation of the relative costs of the situation-based alternatives (time, danger, dollars, mental and physical energy required).

Thus, informed procedural decisions require strategic knowledge. Once a procedure such as measurement taking has been selected, using the procedure effectively depends on system knowledge such as knowing how to read and interpret the measured property. Measurement taking demands such as these and the knowledge needed to assess the conditions under which the skill should be exercised are derivable from elements in the PARI nodes and rehashes. The generation of skill definitions for a job domain serves to describe in detail exactly how procedures are executed, how systems are modeled internally, and so forth. Such detailed characterizations constitute the most explicit cognitive models that provide input to complex skills training programs.

Identification of Instructional Targets. The instructional goal of this early training study was to advance novice troubleshooting capabilities by enabling them to use coordinated procedural, strategic, and system knowledge in increasingly sophisticated ways. The performance components targeted by the instruction were those that clearly differentiated novice from intermediate and expert performances as revealed by the PARI analyses. They consisted of three types of procedural skills, or actions executed on the avionics test equipment: measurements, computer diagnostics, and swapping. Experts were able to use all three procedures and execute them under the appropriate conditions. Intermediate technicians were less likely than experts to take measurements when appropriate and made heavier use of computer diagnostics and swapping. The preferred troubleshooting method of novices was swapping, regardless of the



conditions. These performance differences provided a three-tiered learning trajectory on which to base the instruction.

The performance differences described above can be explained in terms of the "sufficiency" and the "efficiency" of procedures, or actions taken on the equipment. A procedure is said to be sufficient in a particular situation if it accomplishes the current goal by allowing the targeted circuitry to be thoroughly examined and eliminated from further consideration as the source of the fault. A procedure is efficient if it is the best procedure to use among a number of alternative procedures, each of which is sufficient to accomplish the goal. One procedure may be more efficient than another because it takes less time, less physical effort, less mental effort, is safer, provides more information about the system, and so on. In other words, an efficient procedure is less costly and more informative than an inefficient one while producing the same benefit. Since experts have more procedural options available to choose from, they are more concerned with the efficiency of procedures than novices who tend to settle for sufficiency when choosing procedures. The sufficiency-efficiency distinction makes salient the system and strategic knowledge associated with the use of each procedure because it is this knowledge that gives rise to the availability of procedural options.

To illustrate, consider the system knowledge demands imposed by swapping, the use of computer diagnostics, and measurement taking. Given that the goal of all troubleshooting actions is to investigate some part of a signal path, then all three procedures require at a minimum the ability to identify the components on the circuit path to be investigated. Swapping requires the least amount of related knowledge for its execution. It is the preferred method of novices presumably because of the low knowledge demands. One must simply identify active components and serially swap them until the fault is eliminated. By comparison, using computer diagnostics to eliminate parts of the circuitry from consideration requires more system knowledge since the technician must know something about the system functionality in order to select an appropriate diagnostic test to run. Further, to interpret its result, one must know how the circuit used in the diagnostic software compares to the circuit in which the fail originally appeared.

Measurement taking requires still more system knowledge since the technician must be able to manually manipulate the equipment to access the circuitry to measure. This means determining details of the faulty circuit, such as pin numbers on cables or circuit cards or relay contact numbers. In addition, taking measurements requires knowledge of the signal properties one should test for, and selection of an appropriate measurement device. There is also a key companion procedural skill associated with measurement taking, namely the capability to access these system details in the technical documentation, a skill that is not necessarily required to run computer diagnostics.

In sum, choosing an efficient procedure depends on knowledge of the costs associated with using alternative procedures, which in turn depends on knowledge of the system. Although swapping may be a sufficient procedure to use under a wide variety of circumstances, it is not always efficient since (for example) it may cause damage to equipment, it may be physically difficult, or the cost to replace the swapped component may be high. If an appropriate diagnostic is available under those conditions, using the computer to test the targeted circuitry might be more efficient. If not, then efficiency may dictate taking a measurement.

Based on these PARI findings, three performance levels were identified as the approximations of skilled performance to be tutored in this proof-of-principle study. At the first level, the instructional goal was to teach trainees how to identify the components on the signal path where a fail had been encountered. At this initial level the task was to build a device representation of the failed test as a mental model for guiding later troubleshooting actions. This instructional focus is consistent with our findings that experts' system knowledge provides the basis for their procedural flexibility. At the second level, the instructional goal was to get students to choose a procedure for investigating each component on the active path that was sufficient for eliminating it as the source of the fault. At the final level, the goal was to teach trainees which procedure was most efficient for investigating each component under the prevailing circumstances.

Training Methodology. The study was conducted as follows. A human tutor posed troubleshooting problems to novice technicians who were then asked to isolate the fault step by step. PARI records were generated by the tutor who asked technicians at each step for an Action, a reason for the Action (Precursor), and what the outcome (Result) of the Action meant (Interpretation). Trainees were instructed to generate device model sketches to illustrate their solution steps. Each technician received individual tutoring on three to five troubleshooting problems, each requiring approximately one hour to solve. The number of problems presented depended on how many problems it took for a given subject to move through the three instructional levels described earlier.

Each of the instructional goals was pursued individually in the tutoring sessions. A trainee was required to demonstrate if s/he could reliably meet the first goal (identify the components on the active circuit path) before tutoring on the second goal (sufficiency of procedures) was addressed, and so on. The human tutor determined when an instructional goal was met by using rules to diagnose students' weaknesses at each level. For example, a trainee was judged as knowing how to identify components on the active path if her/his problem solution contained explicit references to the components that satisfied the major functionalities of the system, namely, signal generation, routing, and measurement. Similar diagnostic rules were developed for each of the other two instructional levels as well.

Each diagnostic rule had associated with it a set of "querying" hints that provided a structure for the tutor to engage in a type of Socratic dialogue with the student. This occurred when a trainee needed assistance in meeting a given instructional goal (i.e., when a weakness was diagnosed). The content of these hints was derived from the skill definitions for the three troubleshooting procedures. The structure and form of the hints were driven by pedagogical principles such as scaffolding, active learning, and teaching of global before local skills. The first hint simply queried the student for the knowledge lacking in her/his problem solution, e.g., what is the measurement device in this problem? If s/he failed to answer the question correctly, a second query hinted at where the necessary information could be found. If the student still failed to generate the necessary information, s/he was directly told where the information could be found.

If this query was unsuccessful in eliciting the information, the student was told what the missing information was, and then asked why an expert would find that information relevant in solving this problem. If unable to give the reason, the student was told the reason by the tutor. An example of the type of tutor-trainee interchange that occurred is shown in Table 8.

Table 8

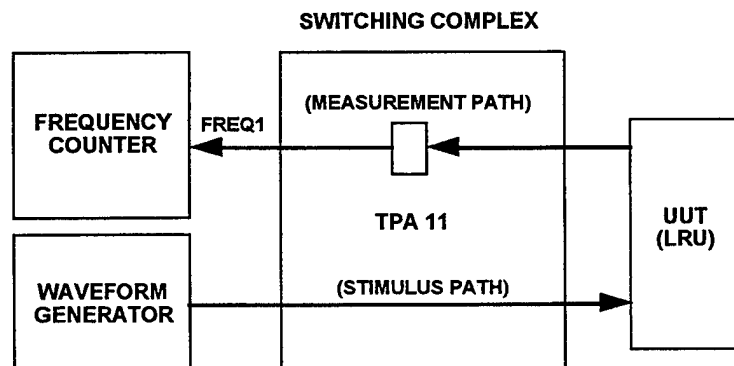
*Sample student-tutor dialogue (Pokorny, in preparation).*

This interchange begins when the student is diagnosed as having a weakness in his ability to identify the components of the active circuit path (Instructional Goal 1). The student incorrectly interprets a piece of technical data, in this case, a computer statement, as specifying the path of the stimulus signal rather than the path of the measurement signal. The tutor directs the student's attention to where the needed information can be found. The computer listing is shown below for clarification, along with a diagram of the circuit involved in this fault.

- TUTOR: Do you think the signal is going into TPA11 [a relay] from the UUT or going out of it toward the UUT?
- STUDENT: I think it's going out.
- TUTOR: O.K. Look at this ROUTE statement again where it talks about TPA11. What is it hooking up? [The tutor is attempting to get the student to determine whether the path through TPA11 is the stimulus or the measurement path.]
- STUDENT: It's routing the signal through TPA1 to FREQ 1, if I'm reading it right.
- TUTOR: How is it that you have identified two paths through this one relay [one path going to the UUT and one path to FREQ 1]?
- STUDENT: For the waveform generator [a stimulus device], you have a CONNect statement, so there is a relay that is connected--the stimulus device would usually be sending something out to the UUT.
- TUTOR: So you've got the ROUTE statement, and this CONNect statement doing something. What is the ROUTE statement doing?
- STUDENT: The ROUTE statement is routing the signal through TPA11, so I guess it would be input to the measurement device.

FAPA LISTING

```
DISCONN 'WFG' OUTPUT NO SP
PROG 'WFG' FOR 3.3 V, 1 HZ FREQ,
  SINE WAVE, NO OFFSET NORMAL
CONTIN MODE, INTERNAL
ROUTE 'FREQ1' INPUTB FROM TPA
  DIRECT FEED IN (11) TP
CONN 'WFG' OUTPUT NO SP
START 'FREQ1'
WAIT FOR 2 SEC
READ 'FREQ1'
CMP RESULT, LL 40 MSEC
IF (GO), GOTO 156500
DISPLAY 'UUT FAILED TEST 1560'
```



To evaluate the effectiveness of this cognitive model-based instruction, seven novice Air Force avionics technicians were administered verbal troubleshooting tests in an immediate posttest, as well as a delayed posttest. The PARI procedures were again used in developing the test problems and in collecting the data. The troubleshooting test problems were different on each occasion, but belonged to the same class and difficulty of problems on which the trainees had been tutored. Progress of their learning was assessed both in terms of the sufficiency of their action--that is, whether they sufficiently investigated all suspect pieces of the equipment (levels 1 and 2 of the instruction)--as well as the efficiency of their actions--that is, whether they efficiently collected relevant information while conserving time and resources.

**Results.** Results showed statistically significant improvements in both areas, with particularly dramatic gains in efficiency. Mean scores are plotted in Figure 8. The group's sufficiency in examining all suspect parts of the equipment improved from a pretest mean of 84 percent correct to a posttest mean of 100 percent. The delayed posttest mean was also 100, indicating the improvement was retained over several days (a weekend). The group's efficiency in fault isolation improved over twofold. The pretest mean for efficiency was 37; the initial posttest mean was 92, and the delayed posttest mean was 93.

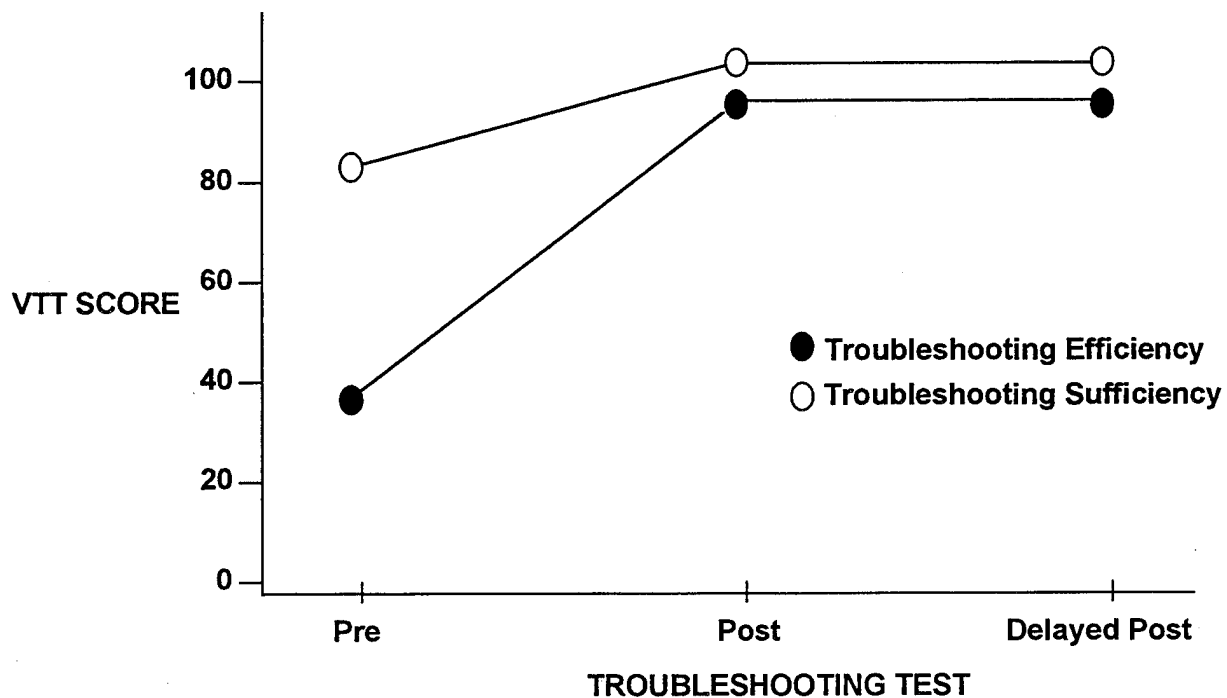


Figure 8. Mean sufficiency and efficiency scores on pre- and posttests.

Although no control group was used in this study, these results are consistent with the conclusion that data from a PARI analysis can effectively focus instruction on the unobservable decision processes that account for efficient solutions and the reasons behind problem solving steps. The course of skill acquisition is likewise made salient in cognitive models across proficiency levels, which appeared in this study to enable more informed decisions about instructional sequencing. The study described in the following discussion provides perhaps a stronger test of the PARI methodology as an aid in instructional design.

#### Development and Evaluation of an Avionics Troubleshooting Tutor

Instructional Design. A second example of a PARI-based training study is provided by the successful development and field test of an intelligent tutoring system designed to accelerate the acquisition of troubleshooting skill in one of several Air Force avionics jobs. (See Gott, 1989 and Lajoie & Lesgold, 1990 for a detailed account.) The curriculum goals and content of the tutor were derived from detailed PARI-like cognitive analysis that contrasted the performance of skilled with less-skilled apprentice technicians on realistic fault isolation tasks (Gitomer, 1984, 1988; Glaser et al, 1985; Gott, Bennett, & Gillet, 1986). Performances for this range of technicians were represented with a problem space-based formalism (Newell & Simon, 1972), in which alternative sequences of PARI steps were represented in a hierarchical structure to provide multiple solution traces through a problem space (Glaser et al, 1985). From multiple traces, it was possible (for a given classes of problems) to abstract the hierarchies of plans and actions used by most technicians. The intelligent troubleshooting tutor (called Sherlock) was built from these prototypical (PARI) structures. Its design is based on the same approach underlying the proof-of-principle study: expert models of performance provided the ideals used as instructional goals; less-than-expert performance data provided the basis for a curriculum progression; finally, the instruction took place in an active, problem-oriented learning environment designed to foster complex skill acquisition.

Instructional Targets. Sherlock's principle instructional goal is tied to the cognitive activity that is required to understand the processes that define a test being run on the avionics test

equipment. These processes were described in the Stage V PARI procedures (see Section III, Figure 6). Their understanding requires that the technicians identify the active components of the circuit involved in the test. The reader may recall that identification of active equipment components was also the first instructional goal tutored in the proof-of-principle study. Lesgold, Lajoie, Bunzo, and Eggan (1988) refer to this instructional goal as the fundamental mental model to be tutored--the mental model of an electronic test. Sherlock's theory of problem solving follows from this focus: troubleshooting is viewed as "device model-guided plans and actions that are regulated by executive (strategic) control processes." The notion of an electronic test is the conceptual base for the procedural and strategic knowledge.

In addition to targeting the fundamental mental model of the test, the tutor is also directed toward developing the technician's goal structure (plans) for investigating the equipment (given the testing process), the procedural knowledge in the form of specific fault isolation actions that instantiate the top-level goal structure, and additional strategic (control) knowledge to inform decision making and regulate systematicity during problem solving. These instructional goals were identified as pervasive troubleshooting weaknesses among apprentices in the prior comparative cognitive task analyses (see Gitomer, 1984, 1988; Glaser et al., 1985). Those weaknesses were also identified in the cognitive modelling of less skilled performers in the proof-of-principle study and served there as the basis for instructional targets as well.

Tutor Evaluation. Sherlock was evaluated in a controlled experiment at two geographically separated Air Force F-15 flying wings. A total of 32 trainees were tested on a number of technical proficiency indicators to establish matched experimental and control groups at each site. The principal form of assessment used in both pre-and posttesting was the Verbal Troubleshooting Tests. A paper-and-pencil noninteractive test comprised of mini (focused) troubleshooting scenarios was also used. In addition, technicians completed a post-tutor evaluation questionnaire.

During the intervention, the experimental group spent an average of 20 hours working Sherlock's 34 problems. Tutoring sessions were scheduled in 2- to 3-hour blocks that spanned an

average of 12 working days. The control group continued participating in the existing (informal) on-the-job training program during that period.

Tutor Effectiveness. Both combined and site-specific data analyses were conducted (Nichols, Pokorny, Jones, Gott, & Alley, in press). Pretest and posttest means and standard deviations for control (N=16), experimental (N=16) and an advanced group of experienced technicians (N=13) are reported in Table 9. Independent sample t-tests showed no significant difference between the experimental and control groups on the pretest, while regression analyses using posttest scores indicate a highly significant effect due to the tutor. As Table 9 shows, the difference between posttest means was over 20 points, with experimental subjects moving to within three points of the advanced group. The comparative experience (in months) for the three groups was 28 months (experimental airmen), 37 months (control airmen), and 114 months (advanced airmen). In site-specific and other related analyses (e.g., paper-and-pencil test), the margin of difference between experimental and control groups was comparable (ranging from 14 to 26 points).

Table 9

*Pre- and posttest means and standard deviations from avionics troubleshooting tutor evaluation (Gott, 1989).*

Group	Pretest		Posttest	
	Mean	SD	Mean	SD
Experimental Group (Tutor Group)	56.93	28.72	79.00	17.39
Control Group (On-the-Job Training Group)	53.40	22.38	58.88	19.67
Advanced Group (Skilled Airmen)	82.15	12.27		



These results support the claim that Sherlock was effective in teaching avionics troubleshooting and accelerating the acquisition of troubleshooting experience. In an attempt to gain a better understanding of what might have accounted for the tutor's effectiveness, technicians who participated in the study were asked to give their reactions to some of Sherlock's features in a post-tutor evaluation questionnaire. In this evaluation, Sherlock received its highest marks for its effectiveness in teaching an approach to troubleshooting, and in improving technicians' understanding of the (stimulus and measurement) functional areas of the equipment and of the routing of circuitry in general. The tutor received comparatively lower marks for freedom of troubleshooting moves within the tutor, usefulness and timeliness of hints and assistance, and meaningfulness of feedback at the end of the session.

The instructional focus on understanding the processes involved in testing a piece of equipment (i.e., the fundamental mental model of a test) thus appeared to be responsible for the training effects observed in this study and the training study described earlier. By targeting system understanding in trainees, this focus provided the conceptual base for the acquisition of procedural and strategic knowledge. In both studies, the PARI methodology was instrumental in identifying the instructional targets and assessing the extent to which they fostered a deep understanding of equipment functioning. Next, we describe a study that addresses how PARI-based cognitive models provide input to training designed to foster breadth of system understanding.

### Transfer of Technical Knowledge

Rationale. The rapidly advancing technologies that populate modern work environments demand considerable mental adaptiveness from human operators and maintainers. Workers in technical domains such as electronics must typically master a broad array of complex systems as well as adapt to a continuous stream of the latest releases/generations/models of those systems. In psychological terms, the performer must be a good transferer of knowledge and skill to be effective. In the context of the BJS Program, developing training that fosters mental adaptiveness

is particularly critical since current Air Force restructuring policies have resulted in broadened maintenance responsibilities that require technicians to maintain multiple aircraft subsystems.

Given the assumption that the ability to solve novel troubleshooting problems on one equipment system requires a deep understanding of that system, a reasonable extension of that claim is that the same type of understanding provides an advantage when learning to troubleshoot a novel equipment system. A recent training study therefore addressed the issue of how technicians' understanding of one equipment system influenced their learning of a related, but relatively unfamiliar system, and their ability to troubleshoot the unfamiliar equipment (Gott, Hall, Pokorny, Dibble, & Glaser, 1990). Technicians participating in the study had from three to ten years of experience in one of two avionic specialties (their "home" job) and at the time of the study, were crosstraining into a third avionic specialty (the "target," or new job). The study thus provided an opportunity to examine learning and transfer in a real-world task for which learners had a great deal of relevant prior knowledge. The PARI-based cognitive models of the three avionics jobs served as a framework within which to interpret individual differences in learning behavior and subsequent troubleshooting performance, as well as a basis for predicting which aspects of the new job would pose the greatest impediments to performance.

The avionics jobs that this study focussed on differ primarily with respect to the test stations used in each job. Although all stations serve the same general function (testing LRU's, or black box components, from the jets), each works on different sets of LRU's. As a result, each avionics job has unique types of test stations. The functions of the test stations are to simulate the electronic signals that the LRU would receive if it were in the airplane, and to measure the signal it produces. The test station thus tests the LRU by sending every signal it is capable of receiving and then determining whether it is responding correctly. When a test fails, the technician must identify the source of the problem and repair or replace the faulty element.

When the fault lies in the LRU, problem solving (i.e., troubleshooting) is relatively simple, because any given LRU has a limited range of functions and components. When the fault lies in the test package (the cables and apparatus which serve as an interface between the LRU and the

test station), troubleshooting can also be achieved by routinized procedures. However, when the fault lies in the test station troubleshooting is complicated by the size of the station--approximately 98 - 324 cubic feet of electronic components; by the tremendous array of signal generation, signal measurement, and signal routing functions it serves; and by the fact that very little of what the test station does is visible to the technician. The cognitive models generated for the three avionics jobs now being consolidated under Air Force restructuring policies describe the problem-solving demands associated with troubleshooting these test stations.

Comparison of PARI-based Cognitive Models. Figures 9 through 11 show skeletal cognitive models for each of the three avionics jobs ("manuals", autos", and "EWS", respectively) at an intermediate level of representation. In all three jobs, system, procedural, and strategic knowledge must be coordinated for troubleshooting to be effective. For each type of knowledge, the expert has access to elaborate hierarchical knowledge structures that range from specific knowledge instantiations to abstractly stated principles.

A comparative analysis of these models reveals the dissimilarities that exist at this intermediate level of specificity. Dashed lines on the figures denote the knowledge components that are demanded by the computerized test stations (automatic and EWS stations) but not by the manually operated station (the manual test station). At lower levels of specificity, similarities between the two computerized jobs would also disappear. On the basis of such comparisons, the EWS job was chosen as the target job in this study because the differences between EWS troubleshooting demands and the other two jobs are greater than for any other pairings of the three jobs. In particular, considerable differences show up at lower levels of specificity between the EWS demands vs the other two models in these areas: the System Knowledge subcomponent "Equipment Structure" and the Procedural Knowledge subcomponent "Actions Using Tech Data." The models thus predict that these two aspects of the EWS job pose impediments to troubleshooting performance for technicians crosstraining from manuals or autos.

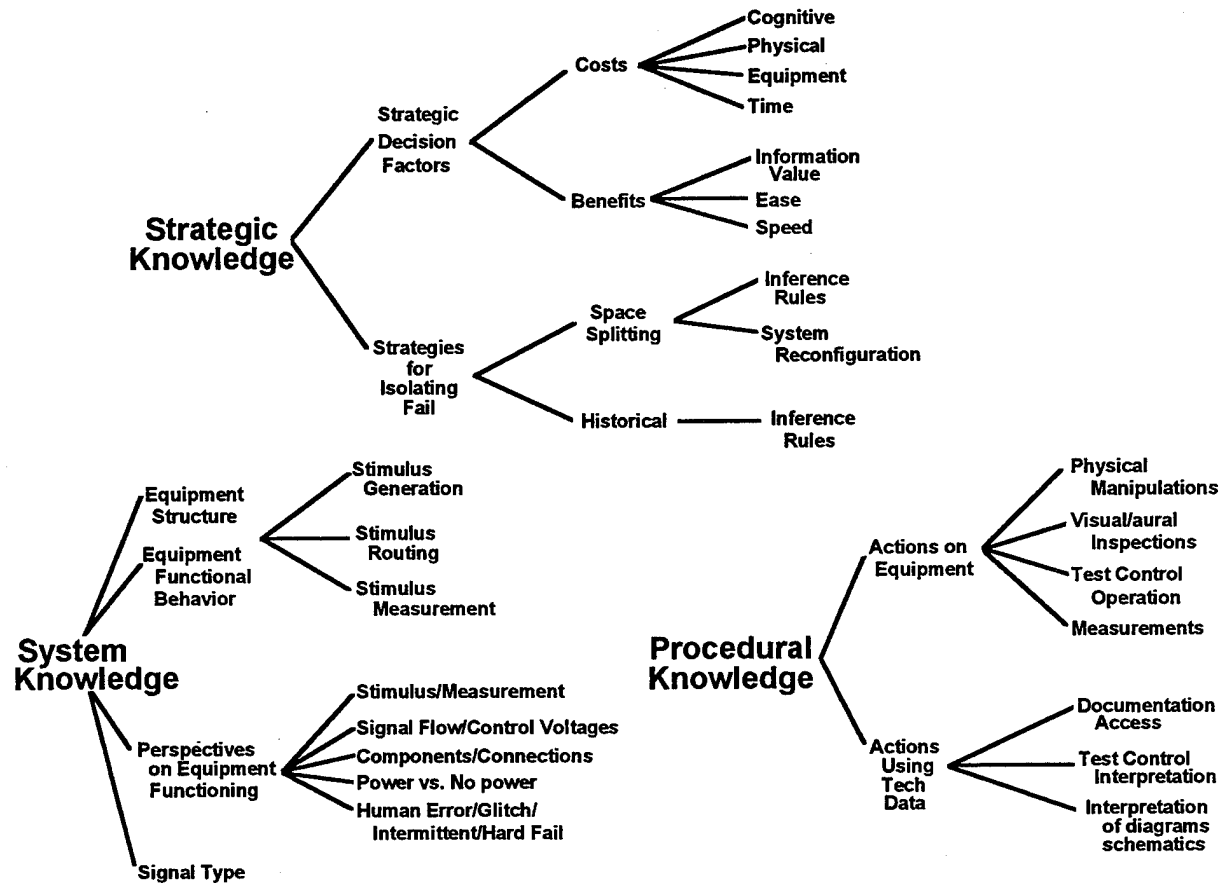


Figure 9. Cognitive model for manual avionics equipment troubleshooting.

**Method.** Three manuals and three autos technicians were chosen for participation in the study on the basis of a pretest in their home jobs and the amount of experience they had with the EWS test equipment. All subjects had only a standard lecture course on the EWS equipment and very little (one to two months) hands-on experience. In addition to being EWS crosstrainees, technicians participating in the study were required to pass a verbal troubleshooting pretest in their home jobs by solving all of the troubleshooting problems presented. No criteria for the quality of those solutions were used as a basis for technicians' participation, only their ability to independently solve the home job problems without the aid of an expert. This ensured that

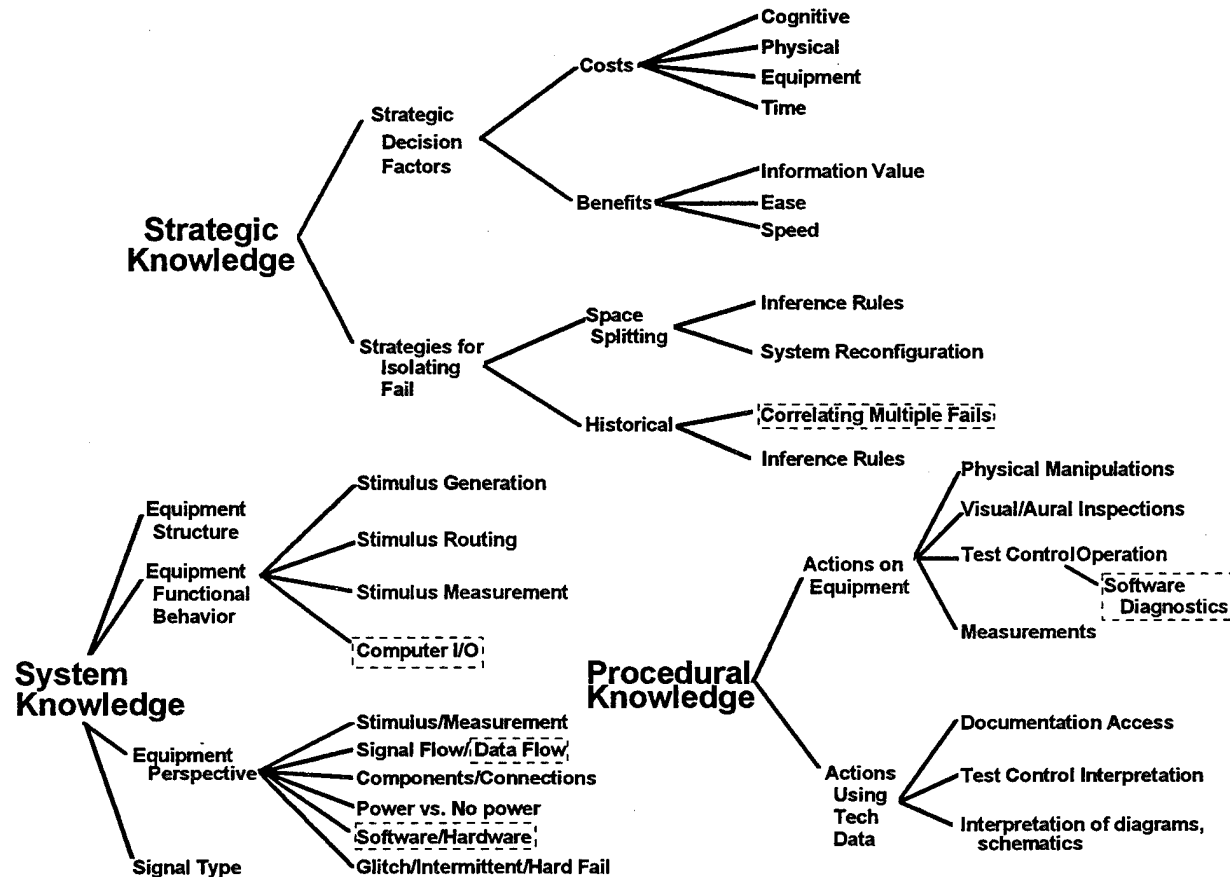


Figure 10. Cognitive model for automatic avionics equipment troubleshooting.

subjects had enough knowledge of their home jobs to transfer to the new job that they would not be overwhelmed by the novelty of EWS troubleshooting task. Thus, while technicians were fairly equal with respect to their experience in the EWS job, they did not necessarily have the same degree or type of knowledge of their home jobs.

The study consisted of pre- and post-tests on EWS troubleshooting problems, separated by a learning phase in which subjects were allowed to ask questions of an EWS expert as they solved learning problems. Subjects were instructed to ask whatever questions they needed answered in

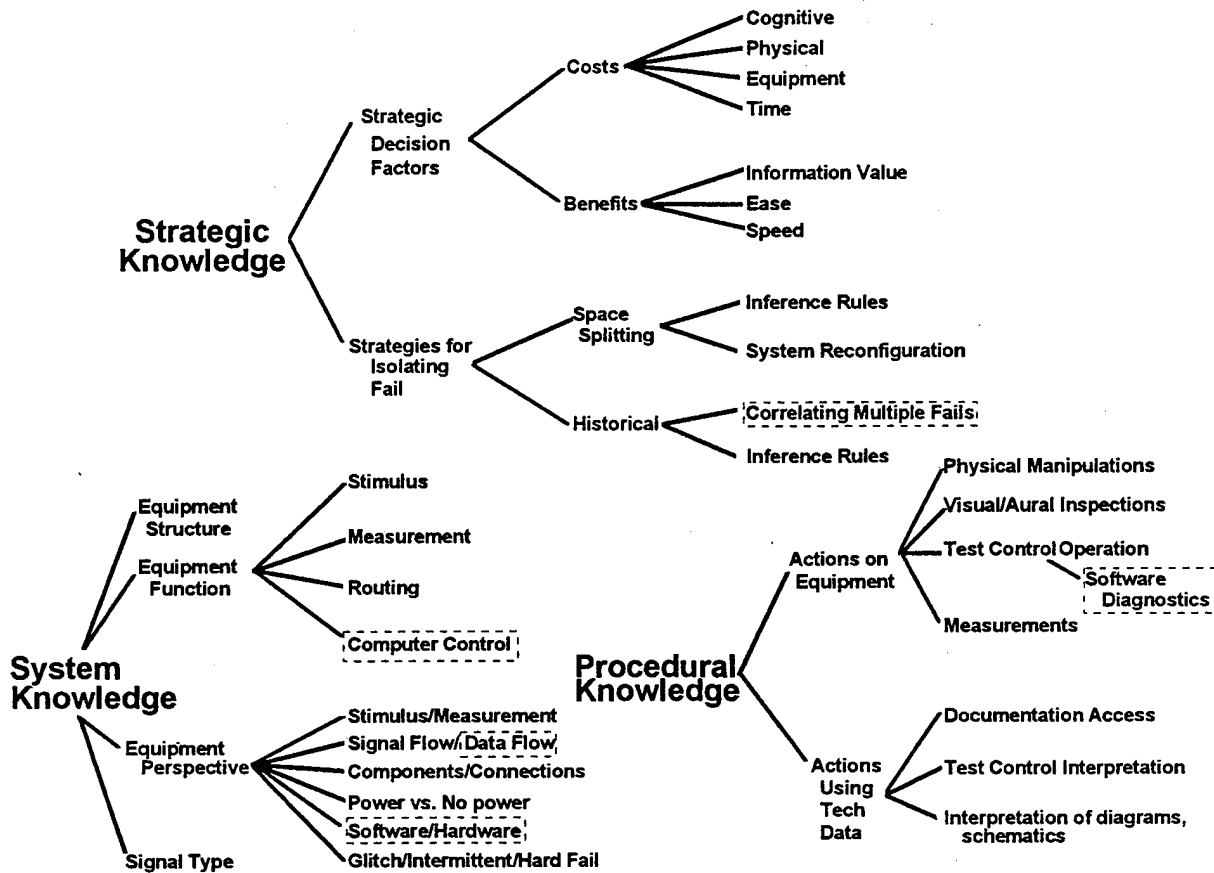


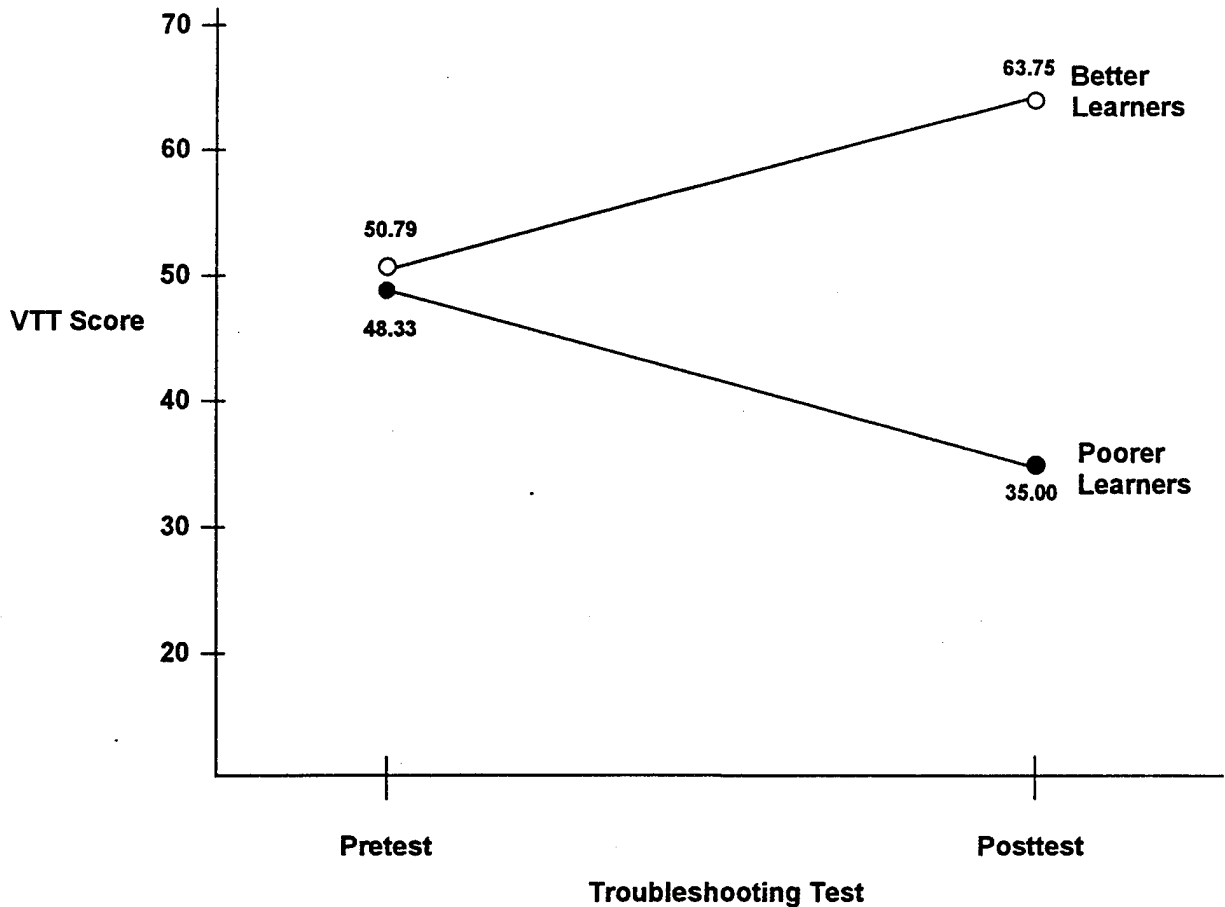
Figure 11. Cognitive model for EWS equipment troubleshooting.

order to make progress toward, and ultimately achieve a solution to the learning problems. They were also told that they would be asked later to solve a set of posttest problems without the help of the expert. The posttest problems varied in similarity to problems presented in earlier phases of the study. Subjects were therefore encouraged to also ask questions during the learning phase that would be generally useful in solving a wide variety of EWS problems, and not restrict their questions to those required to solve the learning problems specifically. All verbal troubleshooting data were collected using the standard PARI format. Subjects' questions to the expert were also recorded, as were the experts' answers.

Results. In order to determine which aspects of the EWS job posed the greatest impediments to troubleshooting performance, an analysis was performed on the types of questions asked most frequently. This analysis involved the classification of subjects' question in terms of the categories represented in the EWS model depicted in Figure 11. The results showed that the great majority of subjects' questions had to do with those aspects of the EWS job shown by the models to be most different from the manuals and autos jobs: the System Knowledge subcomponent "Equipment Structure" and the Procedural Knowledge subcomponent "Actions Using Tech Data."

However, subjects differed with respect to their degree of improvement in troubleshooting the EWS equipment as measured by pre- and posttest difference scores. The mean pre and posttest difference scores for the four subjects classified as better learners (those who showed the greatest pre- to posttest improvement), and the two subjects classified as poorer learners, are shown in Figure 12. The better learners also appeared to be better transferers in the sense that they were able to solve a wider variety of troubleshooting problems in the posttest. Given the quantitative differences found in subjects' EWS troubleshooting performance, associated qualitative differences were examined. These analyses focussed on the learning behavior exhibited during the learning phase, and the ways in which prior knowledge from subjects' home jobs was applied in solving the EWS problems.

All subjects clearly brought relevant prior knowledge to the EWS troubleshooting task. In general, this knowledge took the form of mental models of the test equipment and of the troubleshooting task itself. These models were revealed in subjects' PARI solutions to troubleshooting problems in both their home jobs and in the EWS job in the manner described in Section III of this paper. For the better learners, these models were abstract representations that were used as interpretive structures by good learners to interrogate the expert. These subjects constantly evaluated the adequacy of their models by monitoring their own comprehension of the problems and asked questions to elaborate and adapt their models to the new domain. Thus, a larger proportion of these subjects' questions had to do with aspects of equipment structure and function than those of poorer



*Figure 12.* Mean pre- and posttest scores for better and poorer learners.

learners whose questions focussed primarily on procedures for accessing technical data. The learning strategy of acquiring deeper system knowledge clearly distinguished the better and poorer transferers, suggesting that system understanding provided the flexibility required to solve the posttest transfer problems.

Poorer learners' prior knowledge appeared to be represented in a job-specific (rather than abstract) form. As a result, they failed to adapt effectively to the new domain as seen in their tendency to overgeneralize concepts from their home jobs. Because these subjects failed to think in terms of how differences in the EWS equipment might influence a good technicians' troubleshooting strategy, they demonstrated a high degree of procedural rigidity when solving



problems. These technicians employed the same strategies they tended to use in their home jobs, and refused to deviate from them even when prompted to do so by the experts. This is consistent with the fact that their questions focussed almost exclusively on how to access the technical data they needed to execute troubleshooting procedures, rather than on understanding how the EWS test equipment works and how it differs from that in their home jobs. These preliminary data support the notion that in the domain of troubleshooting, the basis of procedural flexibility and adaptability to novel situations lies in a deep understanding of the system that can accommodate both abstract representations that can be generalized across equipment systems, as well as highly elaborated models tailored to the specifics of particular problem-solving situations.

Conclusions. These results are compatible with Brown's conclusion that "wide patterns of generalization, flexible transfer, and creative inferential projections are all indices of deeper understanding of causal mechanism" (1990; p. 129): technicians who directed their learning toward a deeper understanding of the EWS system, and thus, the causal mechanisms underlying the problem-solving task, showed the greatest improvement in EWS troubleshooting and solved a wider variety of EWS problems. The depth and quality of technicians' knowledge in their home jobs appeared to exert a strong influence on the type of EWS knowledge technicians thought they would find useful, and thus on the degree of transfer.

This study contrasts with the large majority of laboratory studies reported in the transfer literature in that it represents what Gott et al. refer to as a "naturalistic transfer" study (1990; in preparation). That is, all subjects had relevant knowledge to bring to the learning situation and whether or not they would apply it was not an issue in this study. The question was how the depth and quality of that knowledge influenced learning behavior and subsequent transfer.

Because of the complexity of knowledge associated with typical real-world tasks, many laboratory studies of learning and transfer use tasks that are trivial in terms of the knowledge demands they impose (e.g., crossing out p's, then q's in text, or sorting shapes, then colors). Such studies have been criticized because they have little or no functional value to subjects making it unclear why one would expect retention and transfer of such learning. One could argue, however,

that inconsequential tasks are used in laboratory studies precisely because they are trivial: since they require so little knowledge, the researcher has a better chance of adequately characterizing what is to be transferred from the learning task, and controlling the task-relevant knowledge that subjects have available to transfer. Thus, tasks are chosen for which subjects can be given all relevant knowledge in a "learning phase" and for which subjects' prior knowledge is irrelevant. Such tasks are, by definition, trivial and inconsequential.

The problem with those studies is that they fail to acknowledge that real-world learning does not take place in a cognitive vacuum where no prior knowledge is brought to bear. Their results have limited value if they do not generalize to the kinds of learning tasks that people confront in their everyday lives. The naturalistic study of transfer described above demonstrates how the ability to characterize the content of the knowledge that individuals bring to cognitively complex, and moreover, meaningful tasks allows one to draw substantive conclusions about what is transferred, and how the quality and structure of the knowledge base influence the transfer process. The important thing to note in the current context is that the content of subjects' knowledge was identified using the PARI methodology, and interpreted within the framework of PARI-based cognitive models of avionics experts. The tools provided by the task analysis procedures thus allow the study of learning and transfer in tasks involving highly developed, domain-specific knowledge.

### Summary

The studies described in this section constitute tests of the PARI-based cognitive models and thus of the methodology's ability to adequately inform such models. The models were used to identify the instructional targets of the proof-of-principle study and the Avionics Troubleshooting Tutor, and to predict learning outcomes in the transfer study. The effectiveness of training demonstrated in the first two studies, and the accuracy of the models' predictions found in the third study suggest that the methods do in fact capture cognitive components of complex problem solving tasks, and allow meaningful conclusions about how those tasks should be taught. The verbal troubleshooting task used in all three studies is also based on the PARI interview structure,

and provided models of individual student performances which could then be evaluated against the expert model to assess students' skill. These uses of the methodology reflect an accepted principle of practice-oriented training, namely, that testing and training mirror the criterion performance (Gott, 1987).

The methodology is being applied in similar ways to the development of a "Job Family" Tutor (JFT). This prototype, F-15 avionics tutor is designed to teach troubleshooting on the three avionics test stations described earlier in conjunction with the transfer study. Like Sherlock, the JFT represents an example of an intelligent tutoring system. These systems provide individualized instruction by responding to each student's particular strengths and weaknesses based on the tutor's diagnosis of his/her skill. Cognitive models of both the expert and the student inform the instructional content of the tutor, and are also used by the tutor in student diagnosis.

Intelligent tutoring systems represent a relatively recent advance in computer-based training (CBT) and differ from more traditional CBT systems in (among other things) the way that individualized instruction is achieved: whereas traditional CBT systems allow the student to control certain parameters of the instructional interaction (such as sequence and rate of information presented), an intelligent tutoring system guides this interaction based on its model of the expert, its model of the student, and the individual student's actions. The instructional interaction in the latter case more closely parallels that between a student and a human tutor. Although many instructional developers outside the scientific and research community recognize the advantages of this approach, they lack the research tools to implement it. As stated at the outset of this paper, one goal of the BJS program is to develop the tools needed for improved instructional content and delivery and make them available to Air Force instructional designers. One step toward this goal is the documentation of the PARI data collection procedures in this guide.

The PARI methodology has now been used by a number of researchers and individuals in the education community to study a variety of maintenance jobs in the Air Force; these include maintenance of avionic and mechanical subsystems in F-15, F-16, and F-111 aircraft. A future

goal of our Program is to examine the applicability of this procedure to nonmaintenance tasks. To the extent that job environments in our society are becoming increasingly technical and demanding in terms of complex problem solving, we believe the procedure will have broad generality.

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Appendix A  
**Training and Experience Questionnaire**  
(For F15 Avionics Job)

Name _____	Present Organization _____
Rank _____	Present Job _____
AFSC _____	Months in Present Job _____
Phone _____	Months in AFSC _____

1. What are your primary duties in your present job?
  
  
  
  
  
2. What previous jobs have you had in this AFSC? Please describe briefly.
  
  
  
  
  
3. What other AFSCs have you held? Please give brief descriptions.
  
  
  
  
  
4. What type of Air Force training (tech school, FTD, factory school, etc.) have you had in the electrical/electronic field?  
  
Type of course: \_\_\_\_\_ Length: \_\_\_\_\_  
Year: \_\_\_\_\_ (Note: please continue on back if necessary.)
  
  
5. What type of training outside the Air Force (for example, vocational ed program, associate's degree in electronics) have you had in electrical/electronic fields?

Type of course: \_\_\_\_\_ Length: \_\_\_\_\_

Year: \_\_\_\_\_ (Note: please continue on back if necessary.)

6. In your opinion, what are the most important EW areas where experienced manuals and automatics personnel need training for Rivet Workforce purposes?
  
  
  
  
  
  
  
  
  
  
7. In your opinion, what are the most important EW areas where inexperienced manuals and automatics personnel need training for Rivet Workforce purposes?
  
  
  
  
  
  
  
  
  
  
8. What are the primary EW training needs for 3-level personnel when they report to your workcenter?

Appendix B  
Workplace Ecology Questionnaire

AFS: \_\_\_\_\_  
SME: \_\_\_\_\_

1. Effects of mobility exercises
  - a. What are the characteristics of exercises (e.g., how long are they, what conditions are simulated, etc.)?
  - b. What equipment is mobilized and shipped?
  - c. What are the effects of mobility exercises on maintenance requirements?
2. Effects of workcenter equipment usage
  - a. During how many shifts would the equipment be used?
  - b. Is the equipment turned off between shifts? (Circle one)

Yes                      No
3. Mission of organization  
Does the workcenter emphasize its operational or its training mission? (Check one)

☐ Heavy operational emphasis  
☐ Some operational emphasis  
☐ Even emphasis  
☐ Some training emphasis  
☐ Heavy training emphasis
4. Effects of organization's mission
  - a. What is the effect of the organization's mission on the kinds of faults you troubleshoot?
  - b. What is the effect of the organization's mission on the way you troubleshoot?
5. What is the hit rate for diagnostics?

6. Are there temperature-related effects on the equipment? (Circle one)

Yes

No

7. Are there faults that tend to appear when the equipment is first turned on? (Circle one)

Yes

No

If yes, specify -

8. Are there differences between bases with operational and training missions in terms of maintenance of this equipment?

9. What do first termers usually do when the equipment fails? (check one)

☐ Call over a 5- or a 7-level

☐ Consult AFETS or civilian tech rep

☐ Muddle through

☐ Other (please specify)

Appendix C  
**Problem Category Exemplars and Problem Categories**

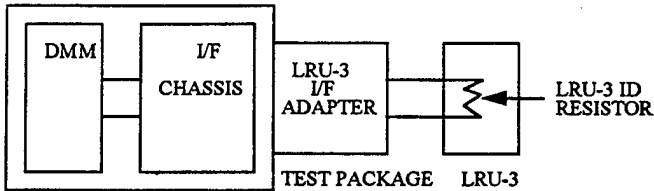
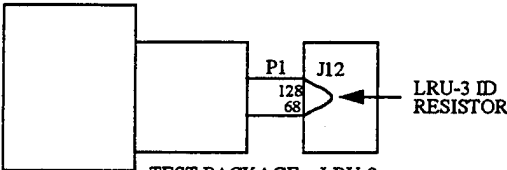
Category Exemplar	Cause/Effect	Problem Category
Monitor Matrix Relay	MMX relay stuck open causing PS-3 to fail confidence test	A/D Switching/Routing
Instrument Select Relay	Stuck relay on instrument select card causes measurement bus failure	
Interface Chassis Relay	Open relay in I/F chassis results in LRU response not being routed to DMM	
RF Switch	Bad RF switch in coax switching panel causes MSS3 failure	RF Switching/Routing
Mixer Diodes	MSS2 failure due to bad mixer diodes	RF Waveform Analysis
Pulse Generator	Bad pulse from pulse generator causes LRU-3 to fail test 323 but OA/FI passes	Analog Waveform Analysis
I/O Card	Basi I/O fails due to bad I/O card	Data Transmission (I/O Logic)
Coaxial Switch Driver	Coaxial switching driver malfunctions causing pulse generator signal output to be routed incorrectly	Digital Data Analysis
Time-Delay Generator	MMX U20 loads down TDG real-time clock causing basic I/O to fail	Clock/Timing
L-17 Self-Test Network	DMM fails VDC confidence test but passes DC calibration due to bad L-17 self-test network	Load

Category Exemplar	Cause/Effect	Problem Category
Unit 4C Power Supply	26 VDC power supply in unit 4C has low output causing RF relays to malfunction	Power Supply
PS-9 Zener Diode	Bad zener diode for PS-9 causes power supply programming failure	
Global error	Constant global error due to full disk	Computer Error Messages
Tape position	Tape header ID does not match keyed-in data because tape is in wrong position	Software Maintenance
RF Cable	Bad external RF cable causes power loss during testing in RF drawer	Connectors
Probe Power Connector	5 VDC probe power connector on DPO is bad causing DPO to be inoperable in remote mode	
Interface Chassis Pin Contacts	External test points fail OA/FI du to dirty pin contacts on I/F chassis	
5VDC Power Display	Keyboard and computer do not have lighted displays because power supply is turned off	Initial Equipment Setup
Bootstrap CCA	No "MAKE DISK READY" indicator on CRT and JSDTD will not load due to bootstrap hangup	Computer Hardware
Replaced A28 Card	LRU-3 fails test 323 due to replacement of A28 card which requires realignment	Alignments



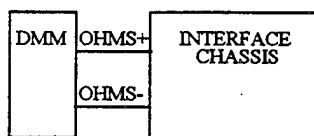
## Appendix D

### Expert Solution Path

SOLUTION PATH	ALTERNATIVE RESULTS/ INTERPRETATIONS (REHASH #2)	ALTERNATIVE ACTIONS (REHASH #3)	ALTERNATIVE PRECURSORS (REHASH #4)
<b>STEP 0 INTERPRETATION</b> This test checks the LRU ID resistor, and the DMM is being used as the measurement device. I will initially focus on the LRU because the LRU ID resistor may actually be bad as the failed test indicates, or a pushed pin in the test package could have caused the fail. Since a pushed pin is more likely than a bad ID resistor, the problem is more likely to be in the test package. I won't focus on the test station initially since troubleshooting the station is more difficult; I'll rule out easier components first.			
			
<b>STEP 1</b> A: Go to TO 12P3-2ALR56-78-1 to look at test description and find out where measurements were made. P: Need to understand the failing test. R: Finds active path is through pins 128 and 68 on J12 of the LRU. I: This tells me what I need to know to eliminate the LRU ID resistor.			
<b>STEP 2</b> A: Remove P1 from J12 of LRU-3, and ohm out the path between pins 68 & 128. P: To see if the ID resistor check is good or not. R: Reading is 1.55 Mohms. I: The problem is in the test package or the test station.			
			
<b>AA1: Measure path at test station access panel.</b> <b>COSTS/BENEFITS:</b> Measuring at access panel would allow you to eliminate the test package as well as the LRU ID resistor. If you're running an LRU when the fail occurs, you suspect the LRU first; measuring at the access panel means you suspect the test equipment. This action is <b>SLIGHTLY WORSE</b> than the original.			
<b>AA2: Run shop-standard LRU.</b> <b>COSTS/BENEFITS:</b> MUCH WORSE than original action because it's time consuming to connect to the shop standard.			
<b>AA3: Replace the LRU ID resistor.</b> <b>COSTS/BENEFITS:</b> MUCH WORSE than original action. You should verify it's bad before you swap it since replacing the resistor is time consuming.			
<b>API1: Focus on the interface adapter.</b> Normally, IPST would have checked the I/F adapter before running the LRU. But testing was started at segment 10 of the LRU tests. So I focussed on the LRU. <b>COSTS/BENEFITS:</b> MUCH BETTER to run IPST before ID resistor tests.			

SOLUTION PATH	ALTERNATIVE RESULTS/ INTERPRETATIONS	ALTERNATIVE ACTIONS	ALTERNATIVE PRECURSORS
<p>STEP 3</p> <p>A: Run IPST (functional check) on the interface unit.</p> <p>P: This checks the internal circuitry of the interface unit for this type of test. Here, it's probably just a straight path.</p> <p>R: All DC tests pass, all ohms tests fail open.</p> <p>I: This result tells you the problem is in the test station because all the ohms checks fail; there is nothing in the test package common to all ohms checks.</p>	<p>AR1: All tests pass.</p> <p>AI1: Fault in cable between interface adapter &amp; LRU.</p> <p>AR2: DC tests fail.</p> <p>AR2: Same interpretation; fault is in test station.</p>	<p>AA1: Manually check out the test package using test package schematics in TO 33D7-50-1-151.</p> <p><b>COSTS/BENEFITS:</b> MUCH WORSE than original action; requires much time, test equipment; normally you would use these tests for troubleshooting.</p>	

<p>STEP 4</p> <p>A: Run OAFI on DMM and see if it passes the ohms checks.</p> <p>P: Since the DMM does all ohms checks, need to make sure it's working.</p> <p>R: Ohms checks are open, and DC checks are O.K.</p> <p>I: Something is wrong with the ohms mode in the DMM. I'm pretty sure that everything up to the instrument select is good because when we ran the LRU, we used the external test points, whereas the OAFI test used internal test points; Since different cards were used in these tests, the inputs to those cards were probably O.K. The problem is in the DMM, Instrument Select, or I/O card for the DMM since those components are common to the two failed tests.</p>	<p>AR1: OAFI on DMM passes.</p> <p>AI1: OAFI and LRU tests could use different instrument select lines. In that case, this result would still point to the instrument select or external test points.</p>	<p>AA1: Could use the patch program to hook DMM up to a different device like the decade box which is a resistor network.</p> <p><b>COSTS/BENEFITS:</b> The original action is the easiest way to check out the DMM, and since the DMM is no more suspect than other components at this point, arbitrarily hooking a device up to the front panel without knowing all resistor readings would fail is strange.</p>	<p>AP1: Instrument select lines are possible.</p> <p>AP2: External test points possible, but unlikely.</p> <p><b>COSTS/BENEFITS:</b> DMM (original precursor) and instrument select lines are MUCH BETTER targets at this point than external test points given the failed ohms tests and the passed voltage checks.</p>
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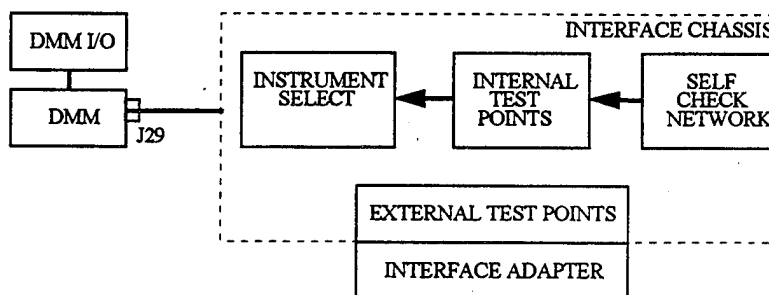
STEP 5

A: Look up description of OAFI test, in TO 33D7-38-77-28-1-1.

P: Need to find out what's involved in the failed OAFI.

R: See drawing (right).

I: External test points were not used in OAFI test.



# SOLUTION PATH

# ALTERNATIVE RESULTS/ INTERPRETATIONS

# ALTERNATIVE ACTIONS

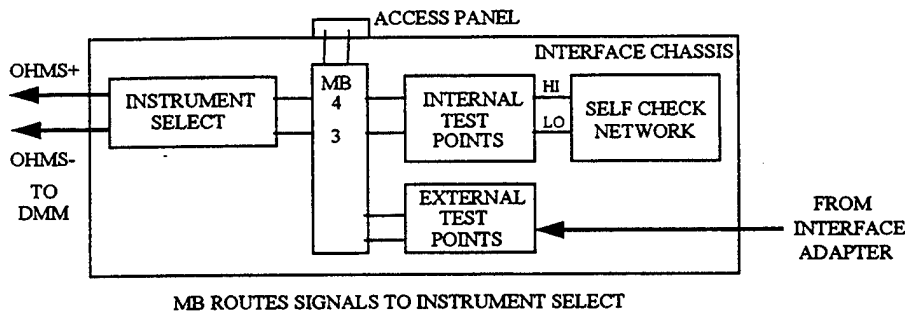
# ALTERNATIVE PRECURSORS

## STEP 6

- A: Disconnect DMM at J29 to take the DMM out of the circuit. Take an ohms measurement at the access panel at measurement bus (MB) 3 and MB4. Look for 8 to 12 Kohms.
- P: If signal is getting to the MB from the self check network, the problem is probably from the instrument select to the measurement device. This check will ensure that both internal and external test points are good.
- R: Reading within limits, +2K ohms.
- I: The circuitry for testing the DMM was good, i.e., the MB, internal and external test points, up to the instrument select. This didn't rule out anything other than what was already expected to be good. Still suspect the DMM or the instrument select card. We were just getting a baseline ohms reading with this measurement.

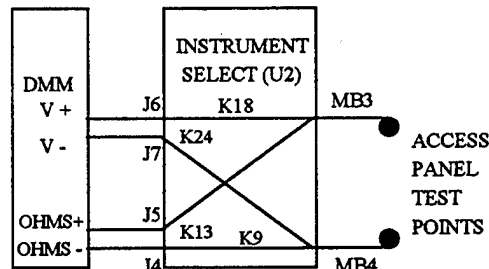
- ARI: Reads open.
- AI1: Reading wasn't getting on the MB; you would have to run OAFI on the rest of the interface chassis. For some reason, the self check wasn't getting connected to the MB from internal test points.

- AA1: Extend the external test points card (U20) and measure its output.
- COSTS/BENEFITS:**  
MUCH BETTER to measure at the access panel since you don't suspect the U20 card anyway and it's also easier.



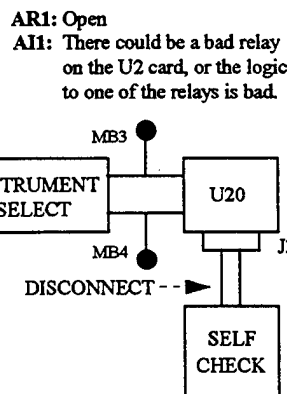
## STEP 7

- A: Go to TO 33D7-38-77-2-2, MMX Functional Organization, and TO 33D7-38-77-28-1-1, DMM OAFI test summary, to find precise path used in failed OAFI test.
- P: Want to know which relays were used on the instrument select card (U2).
- R: K9, K13, K18 and K24 are used.
- I: Now I can check continuity through the instrument select (U2) card and if there's an open, I'll know which relays to look at.



## STEP 8

- A: Ohm from MB4 test point on access panel to connectors on J4 and J5 on the back of the U2 card, after disconnecting the internal test points card (U20) at J3 from the self check network. This allows you to measure from internal test points to input lines of DMM (through the instrument select lines).
- P: Checking for opens in lines going through U2 card to the DMM ohms + and - inputs.
- R: 1K ohms through each connector.
- I: The relays are setting as they should. There might still be something wrong with the card such as a relay being set that's not supposed to be.



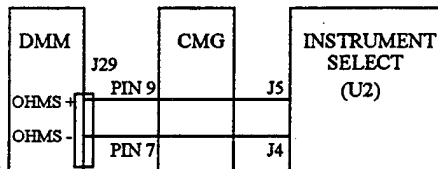
- ARI: Open
- AI1: There could be a bad relay on the U2 card, or the logic to one of the relays is bad.

- AA1: Could have checked the path by probing with the U2 extended, and measuring from the input to the output of the card.
- COSTS/BENEFITS:**  
This action is SLIGHTLY WORSE than the original because there is no advantage to it, and you can damage the card by handling it.
- AA2: With card extended, measure across the relay input to output.
- COSTS/BENEFITS:**  
This has additional disadvantage (besides handling card) that the runs (paths) on the card are not being checked.

## STEPS 8 - 11

The main goal of the original action was to check the instrument select relays. In looking at the total circuit, you could have ohmed out anywhere you could break it down.

SOLUTION PATH	ALTERNATIVE RESULTS/ INTERPRETATIONS	ALTERNATIVE ACTIONS	ALTERNATIVE PRECURSORS
<b>STEP 9</b> <b>A:</b> Ohm check from J4 and J5 (outputs of U2 card) to J29 on the DMM, pins 9 and 7. <b>P:</b> Checking continuity through the CMG back to the DMM. <b>R:</b> When you disconnect the cable from J5, you find the center conductor is pushed in. <b>I:</b> Problem solved.	<b>AR1:</b> Good continuity through both lines. <b>AI1:</b> Could have a shorted relay on the U2 card. <b>AR2:</b> Could have found good continuity through the high line and an open in the low line. <b>AI2:</b> Problem is in the low line (OHMS -) to the DMM.		<b>AP1:</b> Look for shorted relay on instrument select cards.



#### GROUPED ACTIONS (REHASH #5)

ACTIONS	FIRST GROUPING	SECOND GROUPING
1. Look at LRU TO to understand failing test. 2. Ohm out LRU ID resistor. 3. Run IPST on interface adapter. 4. Run OAFI on DMM. 5. Look at OAFI TO to understand failed test. 6. Disconnect DMM, take ohms meas. at access panel. 7. Look at block diagrams TO to identify instrument select relays being used in failed OAFI test. 8. Ohms check from access panel through instrument select relays. 9. Ohms check from output of U2 to the input of the DMM.	1 & 2: Ruling out the LRU 3: Ruling out the test package 4 & 5: Correlating results of multiple tests. 6: Space splitting; confirming interpretation of multiple test results. 7 & 8: Checking instrument select relays. 9: Checking ohms path to the DMM.	1 - 3: Eliminate components external to test station. 6 - 9: Eliminate internal test station components.

## Appendix E

### Problem Set Review by Expert Problem Solvers

As a set, how representative of the problems seen in the shop are these problems?

5	4	3	2	1
highly		moderately		not
representative		representative		representative

Do you think these problems cover all of the important thinking skills in the job? (circle one)

Yes                  No

If not, what other thinking skills are important in this job?

What types of problems would tap these additional skills?

How would you rate the proficiency of a technician who can solve these problems?

5	4	3	2	1
highly		moderately		not
proficient		proficient		proficient

If you rated the proficiency 3, 2, or 1, briefly describe what other skills technicians must possess or other tasks technicians must be able to accomplish for you to rate them above moderately proficient?

How useful are these problems for training technicians?

5	4	3	2	1
very		moderately		not
useful		useful		useful

If you rated the usefulness 3, 2, or 1, briefly explain why the problems are not more useful.

Please write any additional comments you wish to make about the problem set.

## **Scales for Skill Criticality Ratings**

### **Usefulness of Skill**

- 5 = Extremely useful
- 4 = Very useful
- 3 = Moderately useful
- 2 = Slightly useful
- 1 = Not at all useful

### **Learning Difficulty**

- 5 = Very difficult to learn
- 4 = Difficult to learn
- 3 = Moderately difficult to learn
- 2 = Easy to learn
- 1 = Very easy to learn

### **Recommended Training Emphasis**

- 5 = Extremely important to train
- 4 = Very important to train
- 3 = Moderately important to train
- 2 = Slightly important to train
- 1 = Not at all important to train

### Problem Difficulty Rankings

Rank the problems in order of difficulty, with the easiest problem as number 1. Write the difficulty rank for experts in the first column. Write the difficulty rank for first-termers in the second column.

	Expert	1st-Termer
1. A/D Switching/Routing	_____	_____
2. R/F Switching/Routing	_____	_____
3. RF Waveform Analysis	_____	_____
4. Analog Waveform Analysis	_____	_____
5. Data Transmission (I/O Logic)	_____	_____
6. Digital Data Analysis	_____	_____
7. Clock/Timing	_____	_____
8. Load	_____	_____
9. Power Supply	_____	_____
10. Computer Error Messages	_____	_____
11. Software Maintenance	_____	_____
12. Connectors	_____	_____
13. Initial Equipment Setup	_____	_____
14. Computer Hardware	_____	_____
15. Alignments	_____	_____

## Appendix F

### Independent (Advanced) Expert Problem Set Review

Name \_\_\_\_\_  
Rank \_\_\_\_\_  
AFSC \_\_\_\_\_  
Base \_\_\_\_\_

As a set, how representative of the problems seen in the shop are these problems?

5	4	3	2	1
highly		moderately		not
representative		representative		representative

Do you think these problems cover all of the important cognitive skills in the job? (circle one)

Yes                      No

If not, what other thinking skills are important in this job?

What types of problems would tap these additional skills?

How would you rate the proficiency of a technician who can solve these problems?

5	4	3	2	1
highly		moderately		not
proficient		proficient		proficient

If you rated the proficiency 3, 2, or 1, briefly describe what other skills technicians must possess or other tasks technicians must be able to accomplish for you to rate them above moderately proficient?

How useful are these problems for training technicians?

5	4	3	2	1
very		moderately		not
useful		useful		useful

If you rated the usefulness 3, 2, or 1, briefly explain why the problems are not more useful.

Please write any additional comments you wish to make about the problem set.



Is each problem summary accurate? If not, please rewrite the portion of the summary that needs correction.

Circle One

1. A/D Switching/Routing ..... OK as is ..... See correction on summary
2. RF Switching/Routing ..... OK as is ..... See correction on summary
3. RF Waveform Analysis ..... OK as is ..... See correction on summary
4. Analog Waveform Analysis ..... OK as is ..... See correction on summary
5. Data Transmission (I/O Logic) ..... OK as is ..... See correction on summary
6. Digital Data Analysis ..... OK as is ..... See correction on summary
7. Clock Timing ..... OK as is ..... See correction on summary
8. Load ..... OK as is ..... See correction on summary
9. Power Supply ..... OK as is ..... See correction on summary
10. Computer Error Messages ..... OK as is ..... See correction on summary
11. Software Maintenance ..... OK as is ..... See correction on summary
12. Connectors ..... OK as is ..... See correction on summary
13. Initial Equipment Setup ..... OK as is ..... See correction on summary
14. Computer Hardware ..... OK as is ..... See correction on summary
15. Alignments ..... OK as is ..... See correction on summary

Are any of these problems things that technicians in this job at other sites would not see?

Yes

No

If yes, briefly note next to the problem category what is site-specific about the problem.

1. A/D Switching/Routing:
2. RF Switching/Routing:
3. RF Waveform Analysis:
4. Analog Waveform Analysis:
5. Data Transmission:
6. Digital Data Analysis:
7. Clock/Timing:
8. Load:
9. Power Supply:
10. Computer Error Messages:
11. Software Maintenance:
12. Connectors:
13. Initial Equipment Setup:
14. Computer Hardware:
15. Alignments:

Are any of these problems types of things that would only occur on the specific equipment you have at this site?

Yes

No

If yes, briefly note next to the problem category what is equipment-specific about the problem.

1. A/D Switching Routing:

2. RF Switching/Routing:

3. RF Waveform Analysis:

4. Analog Waveform Analysis:

5. Data Transmission:

6. Digital Data Analysis:

7. Clock/Timing:

8. Load:

9. Power Supply:

10. Computer Error Messages:

11. Software Maintenance:

12. Connectors:

13. Initial Equipment Setup:

14. Computer Hardware:

15. Alignments:

Would any of these problems be solved differently at other sites than they are here? (For example, would procedures such as swapping be used more or less frequently?)

Yes

No

If yes, write the type of site where the solution would differ next to the number of the problem, and briefly describe how the solution would be different at these other sites.

1. A/D Switching Routing:

2. RF Switching/Routing:

3. RF Waveform Analysis:

4. Analog Waveform Analysis:

5. Data Transmission:

6. Digital Data Analysis:

7. Clock/Timing:

8. Load:

9. Power Supply:

10. Computer Error Messages:

11. Software Maintenance:

12. Connectors:

13. Initial Equipment Setup:

14. Computer Hardware:

15. Alignments: